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SEISMIC REGIONALIZATION

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ABSTRACT

In the USSR earthquake risk is now officially mapped by division into areas numbered with the degrees of the Modified Mercalli intensity scale, to show maximum reasonably expectable intensity during future earthquakes on ground of the prevailing character. This paper presents and discusses maps on the same plan for the Los Angeles Basin and its vicinity, for California, and for the United States.

The effect of variation of ground from point to point can be shown only on a large scale. This is microregionalization; the map for the Los Angeles Basin is an example. Small-scale regionalization maps require generalization. Prevailing ground is selected, not strictly by percentage of area, but by considering the foundation likely to be used for construction, in mountainous areas mostly small alluvial patches less stable than the surrounding rock.

Regionalization and especially microregionalization can be used in construction and planning, as indicating maximum effects to be considered in designing permanent structures. In adjusting insurance rates, and in designing temporary structures, statistical frequency of occurrence is also involved.

Over small areas, regionalization depends largely on local variation of ground and geology; over large areas, distance from active faults must be considered. Attention should be given to the effect of structural trends and of wave path on the form of isoseismal curves.

Mapping for the Los Angeles Basin area is reasonably definite. That for California is fairly reliable, but less so in desert and mountain areas. That for the United States is in part highly speculative and subject to substantial change.

TYPES OF EARTHQUAKE MAPPING

THE GEOGRAPHY of earthquakes may be represented in at least three distinct ways, according to the application intended:

1. For geological purposes, indicating the distribution of contemporary tectonic activity. Maps show individual earthquake epicenters, or represent statistics on annual numbers in given areas by shading or contouring. Unless due attention is paid to magnitudes, the mapping is likely to be distorted by large numbers of small earthquakes observed in populated areas, or originating near established seismological stations.

2. For insurance purposes, indicating the recorded or expected frequency of earthquake occurrence, together with the expected intensity of shaking. Here the chief

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obstacle is the great irregularity of earthquake incidence in time, particularly in areas of generally minor to moderate seismicity which may be affected by occasional strong shaking.

Mapping of this kind must consider, not only known or expected earthquake epicenters and magnitudes, but the intensity or degree of shaking to be produced by each individual event over the whole area considered, and must include a final estimate of risk, derived from the observed or expected frequency of events in each class and area.

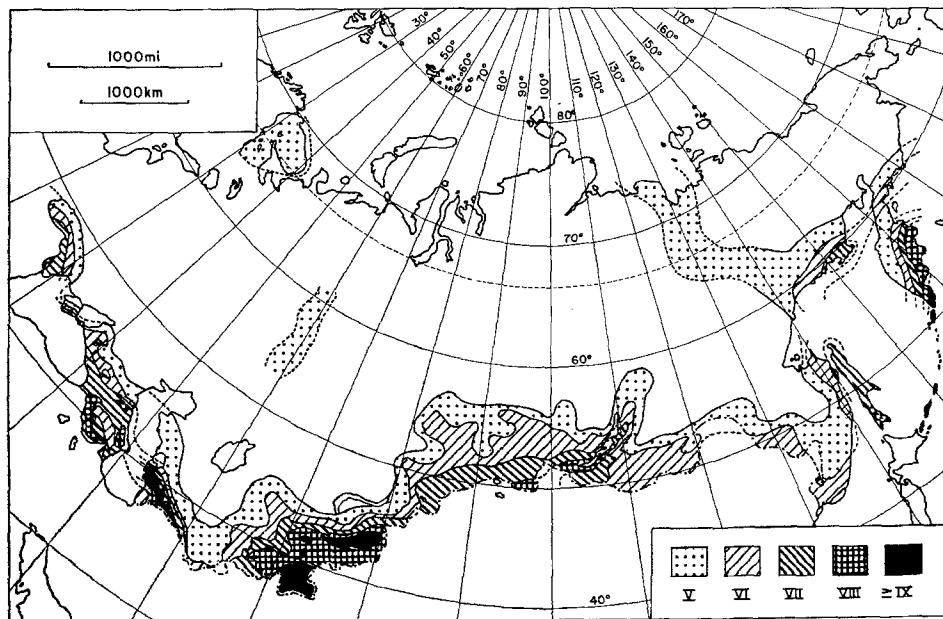


Fig. 1. Regionalization map for the USSR. Redrafted from Savarensky and Kirnos (1955), with some omission of small details.

3. For engineering purposes, giving the maximum intensity to be considered in design of new construction, or reinforcement of old construction, at all points mapped. Such mapping must be based on the probable earthquake occurrences, the distance of each from the point mapped, and finally the character of the ground and its effect on expected intensity.

Compared with mapping for insurance risk, the last procedure is simpler, in that it considers primarily only the expected maximum to be designed for. In detail, serious questions and grave complications arise.

In the USSR this third type of mapping was begun about 1933, and has been developed systematically since 1947 (fig. 1). The authoritative maps (Gorshkov *et al.*, 1949) have official force, and proposed construction must conform in design to specifications for the various mapped degrees of intensity. The procedure is termed *seismicheskoe rayontirovanie*, which may be literally translated as "seismic regionalization." The writer prefers this form to the more obvious "seismic zoning," with the understanding that the meaning is restricted to the type of mapping here described.

STATISTICS AND GEOLOGY

The early regionalization maps for the USSR, drawn up by Gorshkov (1947) and collaborators, were severely criticized by I. E. Gubin (1954) on geological grounds. Although geological considerations had not been neglected, data used for these maps were chiefly historical records of earthquake effects, generally not extending over more than two centuries. Where population is unevenly distributed, unmodified application of historical statistics usually leads to apparent concentration of seismicity in small spots surrounding the largest and oldest centers of culture. Such a distorted result is particularly undesirable for regions like Central Asia and California, where population and industry are now expanding into areas formerly almost unoccupied, some of them in the immediate vicinity of known earthquake sources.

Gubin placed strong emphasis on the need for considering geological evidence of recent tectonic activity. At the very least, stratigraphy and geomorphology in unpopulated regions should be correlated with those of settled areas where there is a history of strong earthquakes.

It appears, however, that in much of the Soviet Union the simplest and most natural application of geological data to regionalization occasionally leads to results difficult to accept, and this has given Gubin's opponents opportunity to challenge his arguments (Belousov, 1954; Petrushevsky, 1955). Both sides have engaged in search for better geological criteria of contemporary seismicity; discussion, still often highly polemical, now centers on this question (Gubin, 1955; Gzovsky, 1957).

Later mapping has been revised to take into account the known earthquakes since 1947. Moreover, earnest effort has been made to use the data of instrumental recordings (there are now 76 established seismological stations in the Soviet Union). Where such recordings refer to large earthquakes in remote areas, they contribute to regionalization in a clear and definite way. Where they refer to small and minor earthquakes, difference of interpretation is still possible; the point will be discussed later in this paper.

The "Seismic Probability Map of the United States" (Roberts and Ulrich, 1950, 1951) prepared for the U. S. Coast and Geodetic Survey in 1948 by F. P. Ulrich with the advice (which he did not always follow) of seismologists in all parts of the country, was not strictly a regionalization map, since it was directed rather to estimate of risk than to maximum intensity. However, it shows areas numbered 0, 1, 2, 3, noted as for no damage, minor damage, moderate damage, and major damage. Although geological data were considered, the basis of mapping was largely statistical. Thus the map shows a circular spot numbered 3 in Montana, corresponding to damaging earthquakes in 1935 (Ulrich, 1936), but ignores other earthquakes and known active structures in the same geological province. The Puget Sound area, rated 2 on the original map, was raised to 3 on revision in consequence of an earthquake in 1949.

The Seismic Probability Map was officially retired in 1952, as "subject to misinterpretation and too general to satisfy the requirements of many users." The same, of course, might be said of almost any scientific result prepared for public use. This action was not taken in consequence of scientific criticism, but as a result of pressure from a business group interested in lower rating in their community. Despite its

imperfections, the map has its proper uses, and in general represents good judgment. It continues to be published as an integral part of the Uniform Building Code (1955). A map for Canada on the same principles was published by Hodgson (1956).

SIGNIFICANCE OF SMALL SHOCKS

Experience in the USSR, as well as attentive study of the data for California or any other active region, shows that regionalization on the basis of surface geology alone is impossible, and that even when surface geology is supplemented by sub-surface geological and geophysical data it does not provide an adequate guide without the use of earthquake statistics, including both historical records and contemporary instrumental observations.

Since large earthquakes are rare, most of the information refers to comparatively small shocks. In applying this to regionalization an important assumption is involved, which in many instances can be shown to be seriously in error: namely, that the frequency of occurrence of small earthquakes in different areas varies with the incidence of great earthquakes, so that the latter are to be expected especially in those areas where small shocks have been most frequent.

With the aid of the magnitude scale, earthquake statistics have been revised systematically (Gutenberg and Richter, 1954; Gutenberg, 1956*a*, *b*). Data for the world may be summarized as follows (Richter, 1958*a*):

Magnitude	Average annual number
9.0 and over.....	0
8.0-8.9.....	2-3
7.0-7.9.....	18
6.0-6.9.....	150
5.0-5.9.....	800
4.0-4.9.....	6,200
3.0-3.9.....	49,000

For the larger magnitudes these figures are based on complete counts over 20 to 50 years; for the smaller magnitudes they represent extrapolation from results in limited areas. In general, these data correspond to the active parts of the circum-Pacific belt, which includes about 80 per cent of the seismicity of the earth. Elsewhere it is not safe to conclude that, for example, where 50 earthquakes of magnitudes 3.0-3.9 occur per year, one of magnitude 8.0 or over may be expected about once in 400 years, while where 500 small earthquakes occur in a year a great one may be expected once in 40 years.

In the California region these proportions are probably roughly correct; in southern California about 200 earthquakes (excluding aftershocks of larger ones) of magnitudes 3.0-3.9 occur in an average year, and the best evidence indicates that great earthquakes may be expected there on an average of about once per century.

Regional differences appear even in statistics of major earthquakes. The following data for large shallow earthquakes are as summarized by Richter (1958*b*):

Magnitude $M = 8.6$ and over, 1897-1955: circum-Pacific belt 15, Alpid belt 3, Pamir-Baikal zone 3, Kansu (China) 1.

M = 7.9–8.5, 1904–1955: circum-Pacific belt 76, Alpide belt 8, Pamir-Baikal zone 3, Kansu 1, Indian Ocean 1.

M = 7.0–7.8, 1918–1955: circum-Pacific belt 480, Alpide belt 49, Pamir-Baikal zone 8, Atlantic Ocean 11, Indian Ocean 11, elsewhere 11.

The Pamir-Baikal zone (which roughly follows the southeastern boundary of the USSR) has had a much higher proportion of the greatest earthquakes than of major shocks in the range 7.0–7.8. The numbers involved are small, so that significance may be questioned on these data alone. Statistics on minor earthquakes recorded instrumentally in the Soviet Union indicate that only in a few limited areas of the Pamir-Baikal zone is their frequency comparable to that of active regions in the circum-Pacific belt (which in the USSR includes Kamchatka and the Kurile Islands).

Statistics for the region of India between 70° and 95° E are of interest. Of the three great shocks (magnitudes 8.6–8.7) listed above for the Alpide belt, two were in India; the third was in Tibet. The same limits include one of the 8 shocks listed for magnitudes 7.9–8.5, and 9 of the 49 of magnitudes 7.0–7.8. Considering the unstable ground of the thickly populated Ganges plain, and the poor quality of much local construction, it is noteworthy that records list relatively few shocks locally damaging over small areas; this suggests that the proportion of shocks of magnitudes 5 and 6 to those of magnitude 8 is less in northern India than in many other seismic areas.

Similar low ratios of small to large shocks may apply to parts of the eastern United States; this possibility adds to the difficulty of regionalization there.

Departures from the normal proportion of large to small shocks in the opposite sense are well known. Certain areas are characterized by the occurrence of earthquake swarms, including numerous shocks of small magnitudes, although no major shock has ever been observed there. Classic instances are the Vogtland region on the boundary between Saxony and Bohemia (Etzold, 1919; Kárník, Michal, and Molnár, 1957), and the vicinity of Comrie in Scotland (Davison, 1924).

CONSIDERATION OF TIME

A tacit assumption often made and frequently overlooked is that the strongest shaking known to have occurred at a given locality in the past will not be exceeded in the future. This involves supposing that a span of a few centuries at most is an adequate sample of tectonic activity. Earthquake chronicles list numerous instances of large shocks in areas where only small ones had been known to occur (Gutenberg and Richter, 1954).

Geological evidence of tectonic activity in apparently quiet areas is of much importance. Major active faults may be practically quiescent over long intervals; thus the section of the San Andreas fault nearest Pasadena, known to have been involved in the great earthquake of 1857, has been associated with not more than 4 or 5 small earthquakes, of magnitudes usually not exceeding 3, in the last 30 years.

Thus, except in areas of high seismicity, it is unlikely that the maximum intensity experienced at a given locality in so geologically short a time as two centuries represents the maximum to be expected in a thousand years. An extreme point of view would maintain that almost any locality may be shaken with intensity IX (M.M.)

in a sufficiently long time. Regionalization in terms of intensity should then be replaced by risk zoning in terms of frequency. Medvedev (1949) has proposed to take the time element into account by subdividing the regions of VIII, for example, into areas in which that intensity may be expected to be reached (1) over a period of centuries, or (2) in a few decades, or (3) every few years. To the engineer the resulting ratings then suggest requirements for permanent or monumental structures intended to stand for centuries, for ordinary construction with a life of the order of thirty years, and for temporary structures of limited use.

CONSIDERATION OF GROUND

Since intensities used in regionalization are based in large part on historically recorded maximum effects, they tend to represent the behavior of structures on the worst ground in a given area; this worst ground is commonly found on the shores of bodies of water, or in alluvial valleys, and these are the usual locations of the older centers of population which furnish much of the data. Engineers (e.g., Nazarov, 1954) have accordingly objected that such regionalization exaggerates the risk, and have called for mapping on the basis of average good foundation, rather than the worst, with supplementary modification when the ground is either better or worse than the assumed average. The practical difficulty which this would introduce, in making the mapping conform not to the observed circumstances, but to ideal conditions different from the real ones, is obvious.

MICROREGIONALIZATION

Regionalization for the Soviet Union was initiated mostly with small-scale maps, showing the great differences in seismicity between widely separated regions. For limited areas the work has been done on a larger scale, and here it is possible to show the variation in local effects due to difference in ground, as well as the consequences of varying distance from earthquake sources. Microregionalization thus satisfies engineering requirements; but to be effective it must be based on accurate geological and soil mapping. Thus a landslide area in granitic rocks must not be mapped and zoned as if it were part of the igneous mass; geological mapping should show the slide as Quaternary or Recent, and the intensity shown should be the same as for other geologically young unconsolidated formations in the same vicinity.

In considering the probable intensity produced by earthquakes from specified sources, such as known active faults, attention should be given to the probable deformation of the isoseismal lines by known geological structures. As is well known, isoseismals representing a given intensity usually are elongated parallel to structural trends. When seismic waves emerge from rock into alluvium, the locally destructive increase in motion appears to be coupled with a "shadow" effect such that intensity further along the same wave path is actually diminished (Richter, 1957).

GENERAL PROCEDURE

In this paper intensities are referred to the Modified Mercalli Scale of 1931 (Wood and Neumann, 1931), abbreviated M.M. Many of the documents cited used the Rossi-Forel scale; intensities named therein are here replaced by the corresponding M.M. values. The USSR regionalization work now uses an equivalent modification

of the Mercalli scale worked out by Medvedev (1953). Intensity on this or any analogous scale is referred to in Russian publications as *ball'nost'* or *sila*; the word *intensivnost'* is used with the meaning of magnitude.

Regionalization maps for the USSR show areas numbered only to IX, taken as indicating probability of IX or over. This is a wise limitation, since even on a large scale it would raise needless difficulties to attempt to indicate expectation of X.

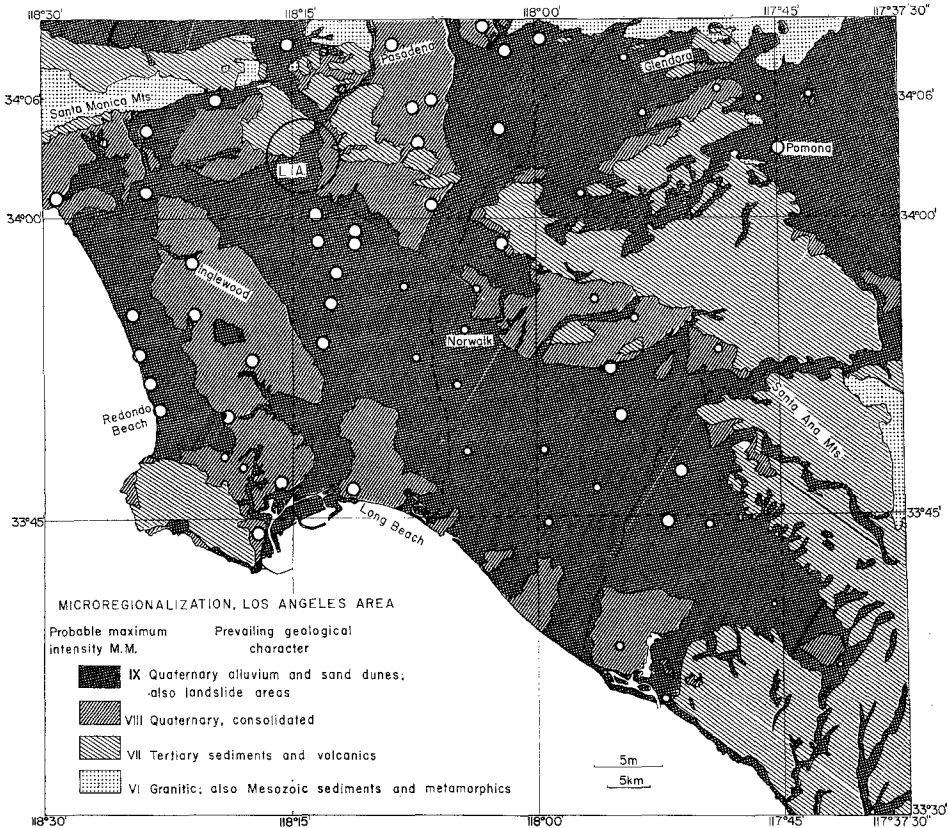


Fig. 2. Microregionalization map, Los Angeles Basin and its vicinity, southern California.

Distinction of this intensity level from IX is not easy even with good data. To the engineer, designing for possible IX is already enough of a problem; the added risk of X or over makes little practical difference.

On the accompanying maps for California and the United States, rating of IX may be taken similarly as indicating IX or perhaps over. On the California map, some of the chief active fault zones have been indicated by heavy bands as areas of special risk, not merely of high intensity, but of exceptional manifestations; see discussion under "California: Geology and Regionalization."

The Imperial Valley has been given special marking to indicate probability that IX may be reached, at any point in the area, more frequently than at points outside it.

On the map for the Los Angeles Basin (fig. 2), IX may be taken as a maximum not likely to be exceeded.

Earthquake magnitudes are given throughout this paper so far as possible on the original basis developed for California (Richter, 1935), or on the M scale used for

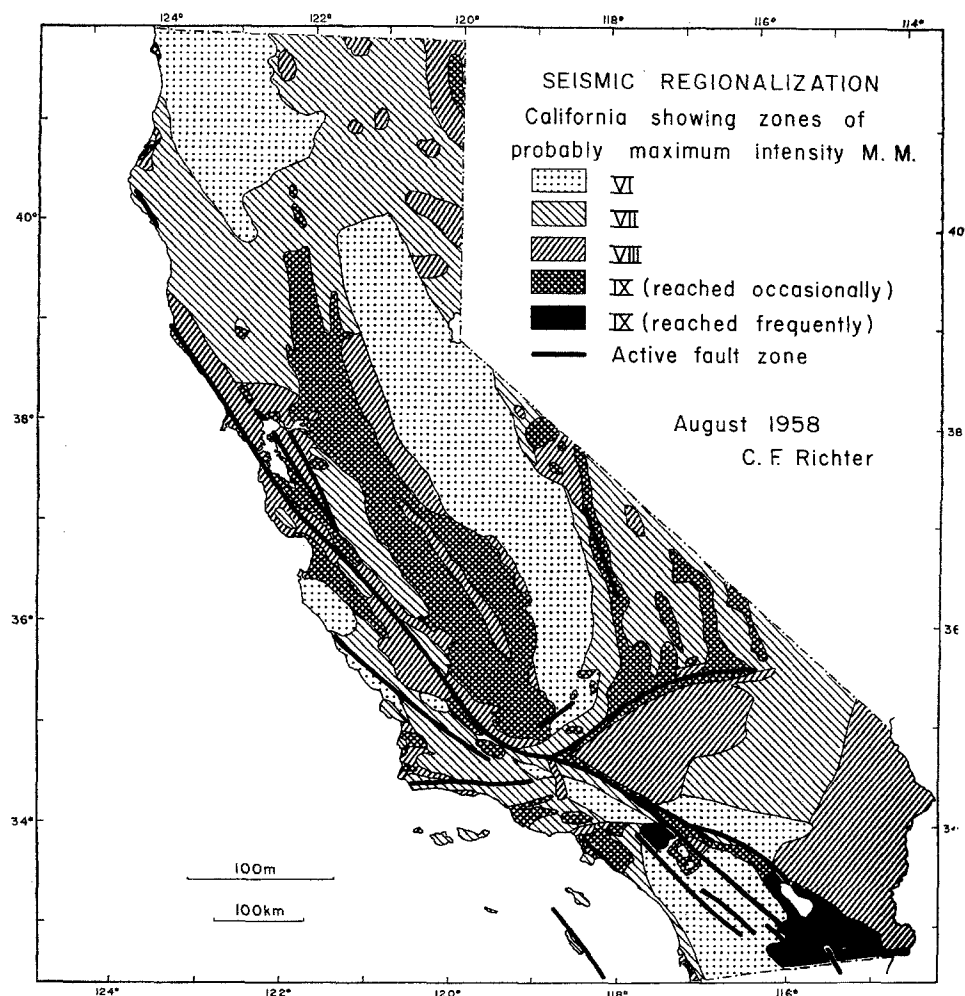


Fig. 3. Regionalization map for California.

distant earthquakes (Richter, 1958*a*, *b*). Where historical data only are available, the magnitude cited is merely an estimate.

Where the same area is covered by microregionalization and by small-scale regionalization, or in transferring the latter to a still smaller scale, problems of generalization arise. These will be evident on comparing figures 2, 3, and 4, representing the Los Angeles Basin, California, and the United States. It is necessary to omit small patches and irregularities which are apparent on a large-scale map but cannot be shown clearly on a small scale. In areas like the vicinity of Los Angeles

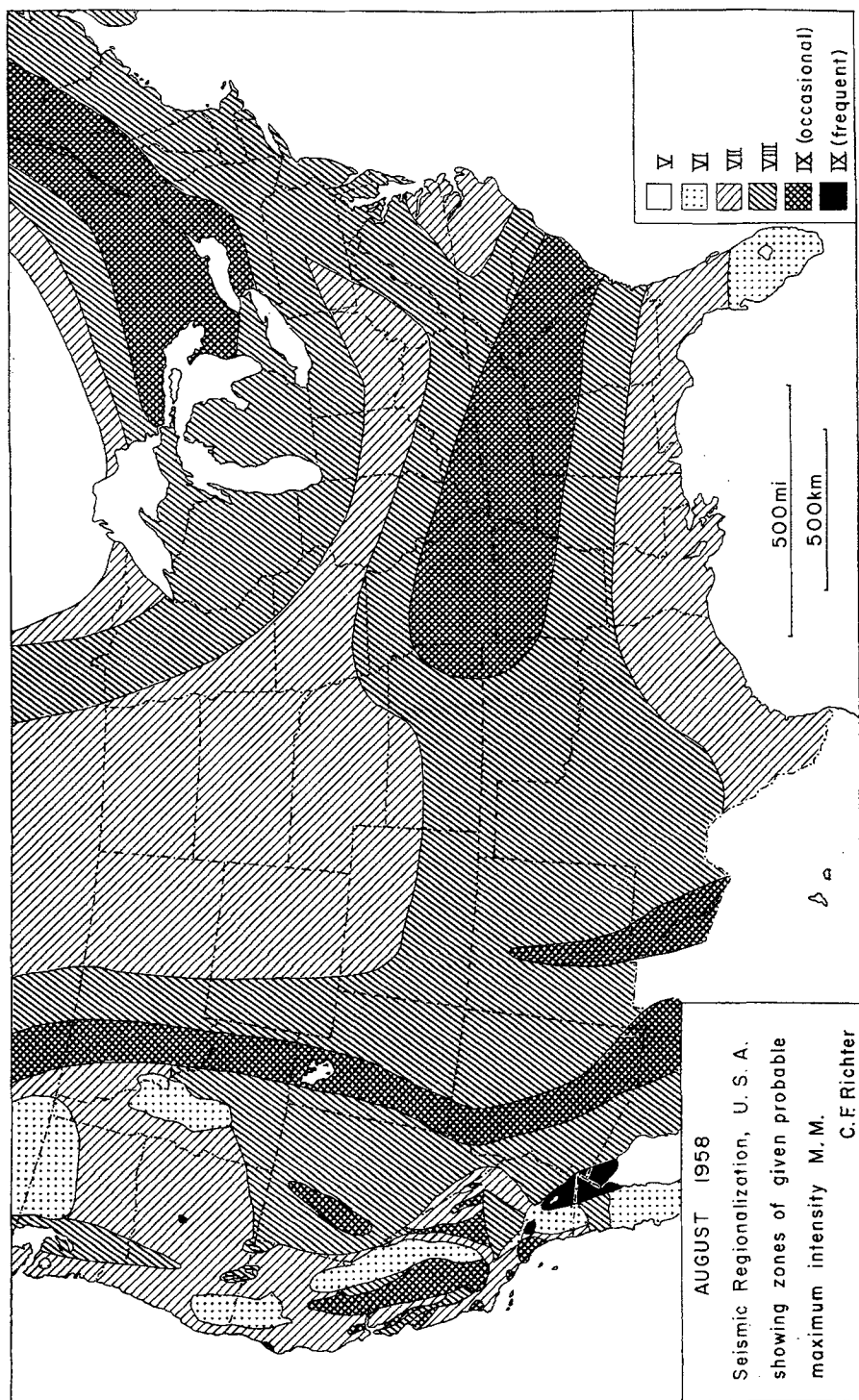


Fig. 4. Tentative regionalization map for the United States and adjacent areas. Outside California, lines between the areas of differing intensity are approximations only.

and Pasadena, where the ground varies rapidly, with alluvium and rock of various ages in close juxtaposition, it is necessary to make a representative choice among the several expectable intensity levels. For engineering use this choice should be representative of the ground under the majority of existing or proposed buildings. Business centers, in particular, are most likely to be located on alluvium, fill, or other unconsolidated ground, so that when the choice of representative intensity is in doubt between two adjacent values, say VI or VII, the higher rating should be mapped.

An important variant of the same problem may be illustrated by conditions near the southwest corner of California, in San Diego County. Most of this area is hilly and mountainous, with exposed rocks of the Southern California batholith, on which a maximum rating of VI is satisfactory. Depressed below the general level are a number of small alluviated valleys; towns and a majority of dwellings are situated in these. For these small spots a rating of VIII or even IX is justified, and is supported by records of damage in shocks with even fairly distant epicenters. On a small-scale map like figure 3 it is only possible to show the rating of VI applying to the general area; to indicate a compromise rating, such as VII, could only lead to misinterpretation. The user of generalized regionalization maps must be prepared to verify the nature of the ground at any particular locality where construction is projected.

Exceptions of opposite character may also appear; such would be provided by a small hill of sound rock in a large alluvial valley, which may be assigned IX in general where the hill individually would deserve a rating of VI.

The intensity scale is best adapted to describing the behavior of ordinary construction of small to moderate size, especially masonry. Effects on tall buildings and on elevated structures such as water tanks are often of different character, and extend to greater distances in earthquakes of large magnitude. This is referred to below in connection with the earthquake of 1952, in discussing regionalization for the Los Angeles Basin and for California, and in remarks on risk at New York and other large cities.

THE LOS ANGELES BASIN: FAULTS AND HISTORY

An example of microregionalization appears as figure 2, representing the Los Angeles Basin and its vicinity. The writer has long been familiar with this area.

As in most of California, the expectable intensity of shaking varies principally with the nature of the ground, and only secondarily with reference to the location of active faults. Most important with reference to the Los Angeles Basin are the San Andreas, San Jacinto, Inglewood, and Norwalk faults.

The San Andreas fault passes about 20 miles north of the limits of the map, trending southeast through Cajon Pass about 30 miles east of the mapped area. Evaluation of earthquake risk in most of southern California involves considering probable effects of a repetition of the great earthquake of 1857 on this fault.

The San Jacinto fault is a highly active branch of the San Andreas system, which diverges from the San Andreas fault on its southwest side. A major earthquake on this fault would reach damaging intensity in some of the mapped area.

The Inglewood and Norwalk faults pass through the area of figure 2 (where they

are not shown), approximately bounding the Los Angeles Basin on the southwest and on the north. The former was the seat of the destructive earthquake of 1933; the latter is known to be active.

Minor faults within the mapped area, and other important faults outside of it, contribute to the probabilities of damaging shaking.

The known earthquake history of the area to the end of 1927 is reported by Townley and Allen (1939). Other details, and extension of discussion to the larger shocks in California and western Nevada through 1950, are given by Wood and Heck (1951).

The following events are the most significant for the present purpose.

1769, July 28. Strong earthquakes felt by the exploring expedition of Gaspar de Portola when in camp on the Santa Ana River, near the present site of the town of Olive. Since the party continued to notice aftershocks for several days after, while traveling northwestward, this was not a local disturbance near Olive, but probably a major earthquake.

1812, December 8. This earthquake wrecked the mission at San Juan Capistrano, just outside the southeast corner of the area of figure 2; it was also damaging at Mission San Gabriel.

1812, December 21. Major earthquake; origin at least 100 miles west of the Los Angeles Basin area. Destructive to Mission Purisima Concepcion, at Lompoc; damaging at Missions Santa Ynez, Santa Barbara, and San Fernando. There was a sea wave, which rose to possibly as much as 50 feet at Gaviota on the coast west of Santa Barbara (Louderback, cited by Wood and Heck, 1951). The source of the earthquake may have been on an otherwise unknown fault under the Santa Barbara Channel.

1855, July 10. Damage to many structures at Los Angeles. Bells at Mission San Gabriel thrown down. Shaking felt at least from Santa Barbara to San Bernardino.

1857, January 9. Wood (1955) rediscussed this event. The present writer cannot accept Wood's judgment that it was of greater magnitude than the earthquake of 1906; the best evidence appears to indicate the reverse. However, it was certainly a great earthquake, and was accompanied by fault-trace effects like those of 1906, extending along the San Andreas fault at least from northern San Luis Obispo County to the vicinity of San Bernardino (Cajon Pass). Shaking appears to have been perceptible over all of southern California, and north at least to San Francisco and Sacramento. Strong and damaging shaking was reported chiefly near the fault, as at Fort Tejon. A report of damage at San Diego is known to be false; however, there was actual damage at Ventura and San Fernando. At Los Angeles, the accounts describe strong and long-continued shaking, with some alarm, but no serious damage.

In estimating the probable effects of a repetition on modern construction, due weight should be given to the numerous reports which indicate motion of long period with large amplitude and of unusual duration. At Los Angeles, one account notes that grapevines hanging from an arbor were seen to swing up and strike the top. The water of the Los Angeles River was thrown out of its bed. This report describes a seiche; similar large seiches appear to have occurred in the Mokelumne and Kern rivers, as well as Kern Lake and Tulare Lake. At some points in the San Gabriel Valley the ground was cracked by lurching, and water emerged.

1894, July 29. Earthquake felt over most of southern California, from Bakersfield to San Diego. Accounts from Los Angeles are exceptionally detailed, and indicate intensity just below the level of general damage, probably M.M. VI. The same is indicated with less assurance at San Bernardino, Santa Ana, and, very interestingly, at Mojave. Although this was certainly a large shock, possibly of magnitude 7, it was assuredly not comparable with that of 1857; the widespread indication of VI suggests the geographical extent of serious damage which might follow a greater earthquake in southern California.

1899, July 22. Origin in all probability near Cajon Pass, on either the San Andreas or the San Jacinto fault. Slides blocked roads in Cajon Pass and Lytle Creek Canyon, on the two fault lines. Serious damage, reported as VIII on the Rossi-Foré scale (VIII-IX, M.M.) occurred at San Bernardino, Highland, and Patton, with lesser damage as far as Pasadena and Los Angeles.

1899, December 25. Large earthquake, with epicenter most probably on the San Jacinto fault in the San Jacinto mountains, and destructive at the towns of San Jacinto and Hemet. It was felt over the area of figure 2, but without damage.

1906, April 18. This great earthquake (magnitude 8.3), destructive in central California, was perceptible as far south as Los Angeles and Long Beach. At the latter place a local seiche, produced in a plunge on a second floor, splashed water out into the street (verbal report to the writer, derived from eyewitnesses); this agrees with the general description of motion in southern California as slow and swaying.

1907, September 19. Damage at San Bernardino and San Jacinto, and slides in the mountains. Information is very incomplete; the epicenter may have been in the Cajon Pass area, as on July 22, 1899, but origin on the Elsinore fault or under the Santa Ana Mountains has been suggested.

1910, May 15. Damage, particularly to chimneys, along the line of the Elsinore fault, from Corona southeast to Wildomar. Some reports indicate minor damage in the Los Angeles area. The Elsinore fault enters the area of figure 2 along the northeast face of the Santa Ana Mountains.

1916, October 22. This shock (magnitude $6\pm$) was felt over much of southern California, including the Los Angeles area. The only observed damage was in the vicinity of Tejon Pass, near the San Andreas fault, to which field workers attributed the earthquake. However, the data would agree equally well with an epicenter on one of several adjacent minor faults, where many small shocks have been located instrumentally in later years.

1918, April 21. Heavily damaging at San Jacinto; epicenter almost certainly on the San Jacinto fault. At Los Angeles it is reported that windows and chinaware were broken, plaster damaged, and walls slightly cracked. The magnitude of this shock was 6.8; an earthquake of higher magnitude on the San Jacinto fault might well be destructive over much of the alluviated area in figure 2.

1920, June 21. A minor earthquake, locally damaging to masonry at Inglewood, led to recognition of the activity of the Inglewood fault.

1920, July 16. Seven small earthquakes, originating not far from the business center of Los Angeles. Street lamps and bottles in drugstores were broken.

1923, July 22. Magnitude $6\frac{1}{4}$. Epicenter in the vicinity of Redlands and San Bernardino, with damage comparable with that of 1899, July 22, but not extending into the area of figure 2.

1929, July 8. Magnitude 4.7. Damage at Whittier, Norwalk, and the vicinity (Wood and Richter, 1931). Epicenter on the Norwalk fault. Maximum intensity VIII-IX M.M. (underground pipes broken) in very poor ground (marshy alluvium).

1933, March 10. Magnitude $6\frac{1}{4}$. The Long Beach earthquake, originating on the Inglewood fault, developed intensity VIII M.M. over most of the alluviated area of the Los Angeles Basin proper, including all except the western part of the largest area of heaviest shading in figure 2. There were a few isolated spots of intensity IX on the worst ground, for example at the coast adjacent to the mouth of the Santa Ana River. Intensity VII extended into the southern part of the Los Angeles business center; and further north there was much damage to weak masonry and in the interiors of many large business buildings, where intensity might be rated between VI and VII. The limit of VI, as represented by damaged chimneys, is drawn by Martel (1936) to include a much wider area. Intensities ranging from VI to VII, with corresponding damage, developed on the sand dunes toward the coast westward. On the principally Tertiary block of the San Pedro Hills intensity was barely VI, contrasting sharply with serious damage near by in San Pedro and Long Beach.

1933, October 2 and October 24. These relatively minor shocks added significantly to the general damage caused by the Long Beach earthquake, since the shaking affected structures already weakened. That of October 2 (magnitude 5.4) had its epicenter on the Inglewood fault, near Long Beach; but that of October 24 (magnitude 4.5) originated on or near the Norwalk fault.

1941, October 21. This minor shock (magnitude 4.9) damaged a few weak structures at and near Gardena, on the Inglewood fault.

1941, November 14. This was also a minor earthquake (magnitude 5.4), but it damaged many buildings in the business center of Torrance. This was cumulative damage; these structures had been damaged in 1933 and inadequately repaired. Seismograph recordings indicate that the epicenter was not on the Inglewood fault, which passes through Torrance, but on a minor fault southwest of it.

1948, December 4. Origin far east of Los Angeles, in the vicinity of Desert Hot Springs. Magnitude 6.5, consequently higher than that of the Long Beach earthquake. Generally felt throughout the Los Angeles metropolitan area, but with no significant damage. Many subsequent reports of minor damage such as cracks in walls and plaster.

1952, July 21. Major earthquake (magnitude 7.7), very destructive in Kern County. Intensities in the Los Angeles area generally from VI to VII; the map prepared by the U. S. Coast and Geodetic Survey (Neumann and Cloud, 1955) assigns VII to the metropolitan center. There was no significant damage in and about Los Angeles to small and weak masonry structures; but damage to interiors of the larger business structures was comparable with that caused by the Long Beach earthquake. This 1952 damage was attributable to the long-period component of shaking (Steinbrugge and Moran, 1954).

LOS ANGELES BASIN: GEOLOGY AND REGIONALIZATION

The base map for figure 2 is the geological map of the Los Angeles Basin area prepared by Woodford *et al.* (1954). The regionalization consists chiefly in translating geology into intensity as follows:

- IX—Quaternary alluvium and sand dunes
- VIII—Quaternary terraces
- VII—Tertiary
- VI—Mesozoic sediments and igneous rock (the latter prevailing granodiorites)

Doubt may well be expressed whether it is proper to associate the various geological units so neatly with even degrees of the Modified Mercalli scale. Slight modifications might be made; thus the Quaternary terrace areas might be scaled a little above VIII. Alluvium and sand dunes might be rated generally somewhere between VIII and IX, reserving IX for the worst ground, chiefly near the coast and in the zones of the Inglewood and Norwalk faults, which would give those faults an expression on the map not apparent in figure 2. The historical data reasonably justify maximum rating at IX, since at any given point heavier shaking may take place in the future than at any time in the known past. There would be no sound reason, however, for indicating X anywhere in the area.

Rating of the granitic foundation no higher than VI is further confirmed by the results of an experiment (Gutenberg and Richter, 1956) in which identical instruments were operated in Pasadena at the Seismological Laboratory (on weathered granitic rock) and on the principal campus of the California Institute of Technology (on alluvium of the terrace classification). Short-period motion in local earthquakes recorded regularly with about 4 times the amplitude on the alluvium as on the rock. Gutenberg and Richter (1942) set up the rough relation

$$\log a = J/3 - 1/2$$

where a is maximum acceleration, and J is intensity M.M. A ratio of 4 to 1 in acceleration (or in amplitude with given period) would then correspond to a difference of 1.8 in the intensity J . The result accords with the assignment of VIII to the Pasadena terrace area and VI to the adjacent granitic rock. Further experimentation by Gutenberg (1956c, d, 1957) extended and refined the general result; Tertiary foundation, as expected, was found to be not so good as granite and not so weak as Quaternary.

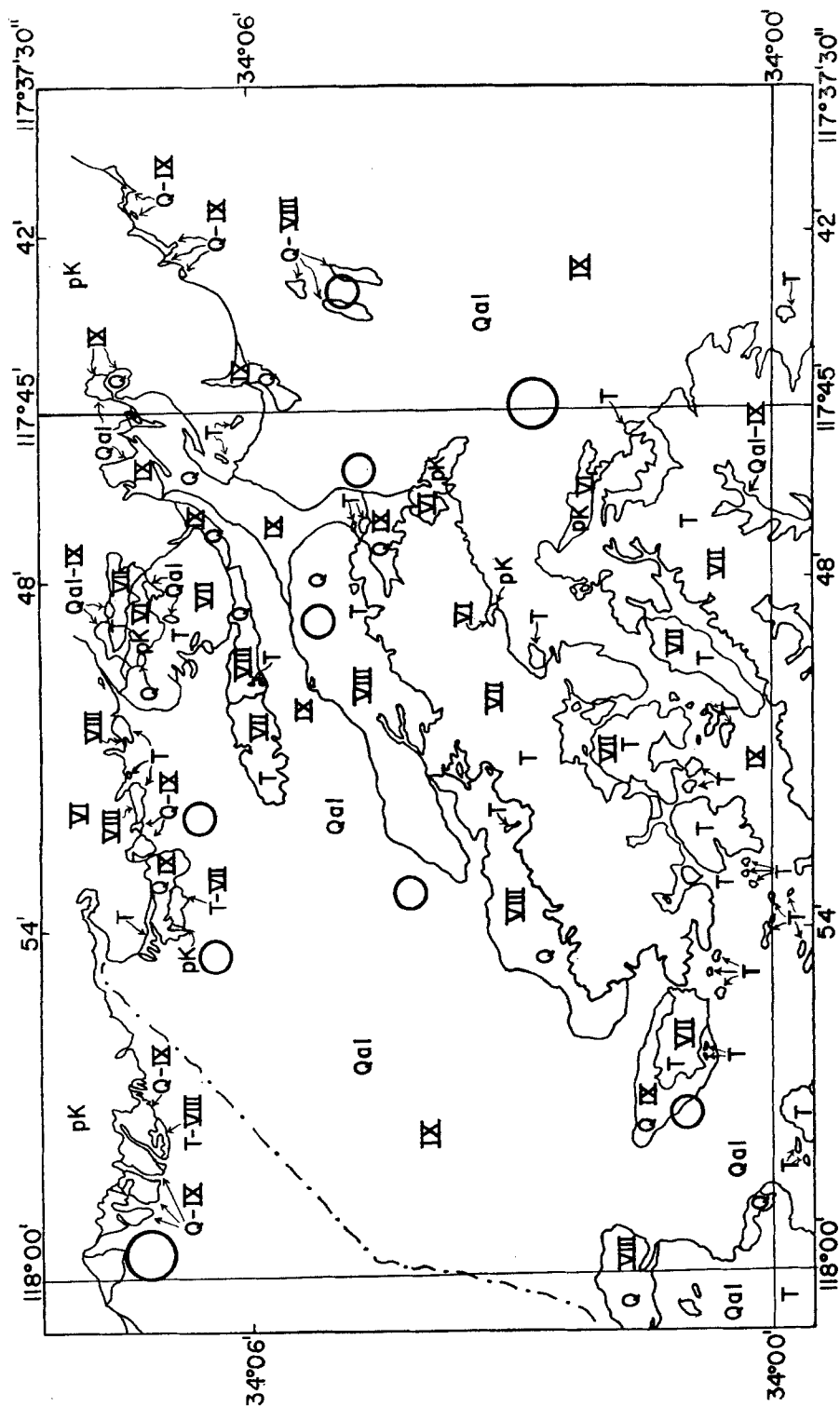


Fig. 5. Part of northern Los Angeles Basin area; detail, showing departures from geological mapping in microregionalization.

Certain departures from regionalization on the basis of geology alone follow from considering the effect of path, particularly in the event of a great earthquake on the San Andreas fault north of the Los Angeles Basin. The general principles have been discussed by the writer (Richter, 1957, 1958b). The well-known higher intensity on unconsolidated ground than on rock is particularly notable where the seismic waves emerge abruptly from rock into alluvium; Neumann (1954) estimated that in such cases amplitudes may increase as much as 22-fold (applying the formula cited above would give a difference of 4 in the intensity *J*, or a rise from VI to X). On this basis, small terrace areas adjacent to the igneous rocks of the San Gabriel Mountains have been assigned IX together with the adjacent alluvium.

Figure 5 shows part of the area of figure 2 in detail, with outlines and lettering indicating both geology and intensity rating. Near the center is a long band of Quaternary terrace material extending out of a large canyon southwestward, and rising into low hills with a townsite (San Dimas). A line dividing this terrace band between IX to the northeast and VIII to the southwest has been drawn somewhat arbitrarily, considering elevation and probable degree of consolidation. IX has also been indicated adjacent to a small outlying exposure of granitic rock.

Some of the small patches within the mountain area marked as Qal and assigned IX are actually landslides. The assignment of IX represents the unconsolidated and unstable nature of the material, with probable enhancement of effects due to shaking; it does not refer to and include the possible effects due to further sliding. While the precipitation of slides can be associated with grades on the M.M. scale, effects on terrain or structures due to sliding should be described in other terms.

Where existing slides are indicated, others may occur, and from this point of view the regionalization map may not properly represent the risk. This is true, for example, along the coast of the San Pedro Hills, where figure 2 shows several large slide areas rated as IX. Along this coast geological conditions are roughly uniform, and new slides may start at other points.

CALIFORNIA: HISTORICAL

Figure 3 is a regionalization map for California. The chief sources for historical material used are the same as those for the Los Angeles Basin; summarized material may be found in Townley and Allen (1939) or Wood and Heck (1951). Remarks at this point include only a few of the events most important in estimating regional risk. Others are cited in other sections.

The effects of four principal earthquakes in large measure govern estimates of earthquake-damage probabilities in California.

1857, January 9. The Fort Tejon earthquake has already been discussed briefly. Information on its effects is fragmentary; moreover, what is known is difficult to apply to present conditions, because of the scantness of population in the region in 1857, and the lack of works of construction comparable with those now existing. Some approach can be made by transferring the isoseismals of the 1906 earthquake on the map to center near Fort Tejon, with the long axis along the San Andreas fault; but this is inadequate in detail.

1872, March 26. Generally regarded as of greater magnitude than those of 1857 and 1906, this earthquake establishes Owens Valley as an area of high earthquake risk. Precipitation of numerous rockslides in the Sierra Nevada illustrates special risk in mountain areas. One large rockfall in Yosemite Valley was witnessed by John Muir, who describes the earthquake there as of great

violence (Muir, 1912). Heavy shaking at Visalia, on the east margin of the San Joaquin Valley, may represent the effect of increased amplitude on emergence of seismic waves from the Sierra mass into alluvium.

1906, April 18, 5:12 A.M. This earthquake may be studied in the report of the California Earthquake Investigation Commission (Lawson *et al.*, 1908). In the heavily shaken area adjacent to the San Andreas fault the effects probably represent the maximum expectable intensity needed for regionalization. The results may be transferred to points similarly situated with respect to other segments of the fault than that displaced in 1906.

1952, July 21. Of lower magnitude than the other three, but equally important for the present purpose, because of the detailed reports available (Steinbrugge and Moran, 1954; Oakeshott, ed., 1955). The effects, moreover, correspond to present-day conditions of settlement and construction. It is important to note the wide extent of damage due to long-period shaking, especially in structures weakened in earlier earthquakes, as at Los Angeles, Long Beach, and Santa Barbara. Regionalization discussion is materially affected by the occurrence of this major earthquake on the White Wolf fault; although the fault was known to exist previous to 1952, it had not been considered as in the same active class with the Elsinore and San Jacinto faults, which are much more clearly expressed in the topography.

Brief notice of some other especially significant earthquakes, in addition to those cited in discussing the Los Angeles Basin, here follows:

1868, October 21. The Haywards earthquake. Faulting on the Haywards fault, along the east side of San Francisco Bay.

1869, December 27. Strong earthquake originating in Nevada; very damaging at Virginia City, Carson City, and other points. Damage in California as far away as Downieville.

1873, November 22. Epicenter off the north coast. General damage to masonry at Crescent City; chimneys damaged over a wide area extending inland.

1885, January 30. Damage in the area of Susanville and Janesville, Lassen County.

1885, April 11. Strong shock felt over a large area; heaviest reported effects about VII M.M. about 25 miles northwest of San Luis Obispo.

1892, February 23. Major earthquake in Baja California. Damage at several points in San Diego County. Intensity at San Diego probably VI-VII. Felt as far north as Visalia.

1892, April 19 and 21. General damage in towns of the western Sacramento Valley, particularly Vacaville, Winters, and Dixon.

1902, July 27. Severe damage at and near Los Alamos, Santa Barbara County.

1906, April 18, 4:30 P.M. Imperial Valley. Chimneys fell at Brawley. A water tank was thrown down at Cocopah (Baja California). Compare 1940.

1908, November 4. Earthquake recorded at many distant stations, which at that date indicates magnitude in the range $6\frac{1}{2}$ -7. Center apparently in Death Valley area; newspapers reported that the continued shaking caused prospectors to leave.

1909, October 28. Magnitude 6- $6\frac{1}{2}$. Intensity VIII (damage to chimneys, etc.) at towns near the coast of Humboldt County.

1923, January 10. Local earthquake in northeastern California and adjacent Oregon (Goose Lake region); maximum intensity V-VI.

1923, January 22. Offshore earthquake causing damage in Humboldt County like that in 1909. Magnitude 7.3.

1927, November 4. Magnitude 7.5. Epicenter off the coast west of Point Arguello. Damage in western Santa Barbara County.

1934, December 31. Magnitude 7. Lower California. Damage in Imperial Valley, chiefly in Mexico.

1940, May 18. Magnitude (as recently revised) 7.1. Faulting along the Imperial fault, extending from California into Mexico (Ulrich, 1941). Damage in all Imperial Valley towns. Intensity IX over a large area; X on the most unstable ground, chiefly alluvium of the Colorado Delta.

1946, March 15. Magnitude $6\frac{1}{4}$. Epicenter in the southern Sierra Nevada near Walker Pass. Damage to structures in alluviated valleys within the Sierra.

1947, April 10. Magnitude 6.4. Epicenter not far from Manix in the central Mojave Desert. Damage to structures scattered over a large but thinly settled area.

1956, February 9. Magnitude 6.8. Epicenter in Baja California in the same region as that of the earthquake of February 23, 1892. Felt over a wide area; fault trace effects developed. Damaging intensity only in Mexico.

CALIFORNIA: GEOLOGY AND REGIONALIZATION

Geological mapping in California is far from uniform. In most of the settled areas, and in mining and oil districts, maps are available in detail on a large scale. At the opposite extreme, thousands of square miles have been mapped geologically only at the reconnaissance level or on a small scale, especially on the eastern desert or in the northern forest region. For these and other reasons the regionalization in figure 3 is not uniformly detailed in all parts of the state.

The best general sources are the publications of the California Division of Mines. The map of 1938, on a scale of 1 : 500,000, is now out of print. A new revised map, scale 1 : 250,000, is in preparation, to consist of 30 sheets, 8 of which are available in preliminary form.

The examples of historical data which have been given will illustrate the conclusion, noted in discussing the Los Angeles Basin, that in California as a whole regionalization depends primarily on the character of local ground, and only secondarily on geographic position. Most points are near enough to one of the principal faults, or to several other active faults, to justify an estimate of IX or over on poorly consolidated ground. On solid igneous rock, such as that of the Sierra Nevada or of the Southern California batholith, nothing suggests a maximum of over VI, except perhaps very locally. The problem reduces in the main to assignment of VII and VIII, and to the representation of the results on a small-scale map.

The zones of the San Andreas and other active faults present a special problem in this type of mapping. In order not to include these zones explicitly in the areas assigned given maximum intensities, they have been drawn as broad and heavily shaded bands. Within these bands risk to construction is of special character, involving not merely the effects of shaking but those of rending, tilting, and shattering by displacements at the surface. The original form of the 1931 M.M. scale assigns fault displacements in firm rock to intensity XII; there is an implied inference that such displacements are accompanied by heavy shaking, which is not to be regarded as a certainty. For discussion see Louderback (1942).

The general adjustment of regionalization to geology in California is the same as that for the Los Angeles Basin; Quaternary alluvium and sand dunes are rated IX, Quaternary terraces VIII, Tertiary sediments VII, Mesozoic sediments and batholithic rocks VI. Near important active zones like that of the San Andreas fault the ratings on sedimentary rock are increased. Some areas in the east and northeast have been given lowered rating representing remoteness from the best-known active faults; however, further eastward the approach to known and suspected earthquake sources in the Great Basin and at the edge of the Colorado Plateau has suggested slightly higher rating.

VI has been assigned to the Southern California batholith, the Sierra Nevada, and the Klamath Mountains complex in the northwest.

The patches of Mesozoic (Triassic and Cretaceous chiefly) assigned VI on the Los

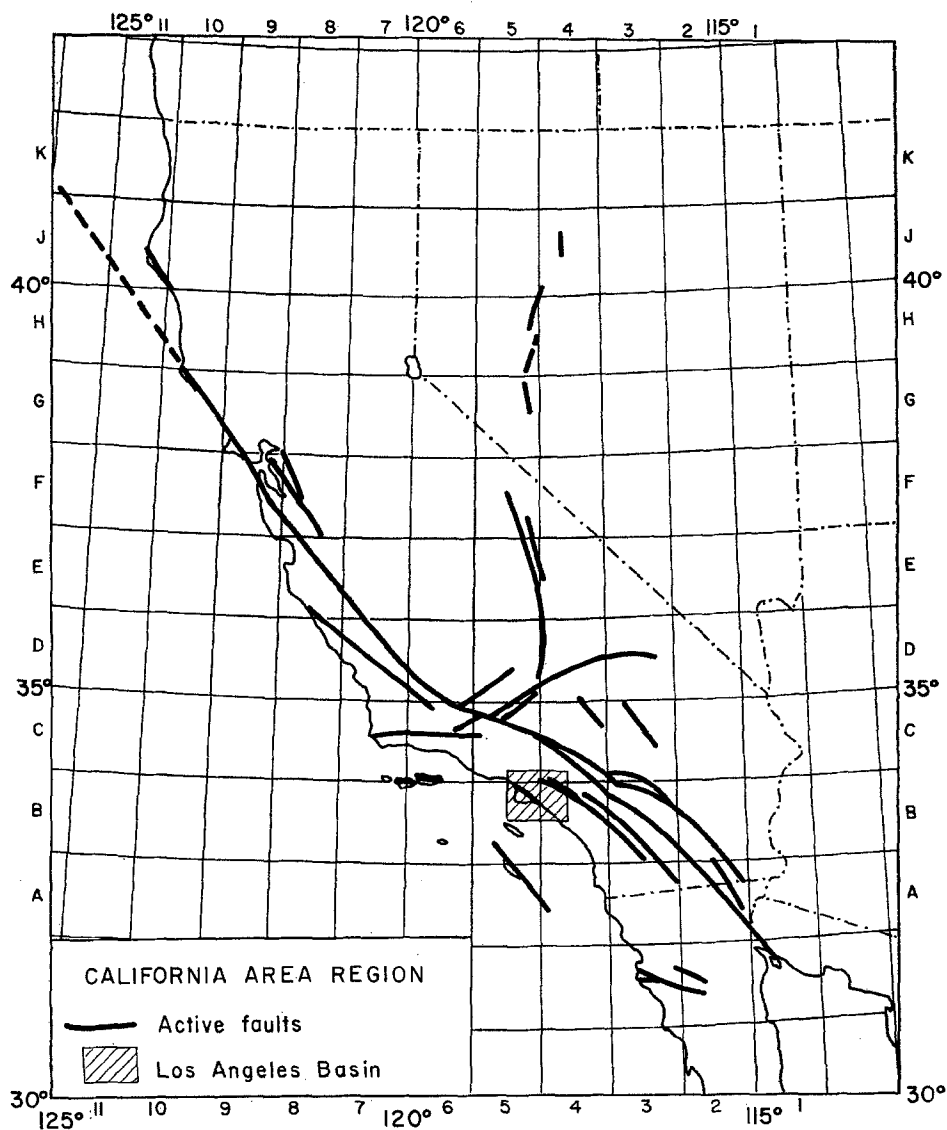


Fig. 6. California, showing faults and location of area mapped in figure 2.

Angeles Basin map have been generalized out on the California map, and similar areas are included with the VII assigned to Tertiary sediments.

In dealing with the large areas of Franciscan (Jurassic-Cretaceous) in central and northern California, general rating has been VII, with VIII at short range from the San Andreas fault. Decision has been influenced by the generally fractured character of the Franciscan, and by the fact that the Franciscan areas are largely hilly, with alluviation surrounding the settlements, justifying increase in the generalized rating on principles discussed above.

Many other arbitrary decisions have been necessary. To forestall misunderstanding, the next section presents detailed notes on each one-degree quadrangle in California. The quadrangles are lettered according to latitude and numbered accordingly to longitude, as shown in the index map, figure 6.

CALIFORNIA: QUADRANGLE DETAILS

These notes summarize regionalization in figure 3 for one-degree quadrangles, singly or in groups. Marginal quadrangles include areas in adjacent states or in Mexico, with results shown on the regionalization map for the United States (fig. 4).

A. 32°-33° N:

1. 114°-115° W. Southeastern corner of California. Divided between IX (Imperial Valley alluvium) and VIII (mountainous area to the northeast); the latter rating in place of VII depends on proximity to the active faults in the Imperial Valley region. The boundary between these zones extends similarly into Mexico and Arizona. In the earthquake of 1940, ground water in the Yuma Valley and adjacent Colorado Delta was disturbed corresponding to X M.M., with much damage to the irrigation system. This represents very unstable ground; all construction there is subject to high risk.
2. 115°-116° W. Southern Imperial Valley, rated IX with frequent expectation; some possibility of X (see A 1). The zone of the Imperial fault is indicated; along this in 1940 many effects referable to X were produced.

In Mexico, the western part of this quadrangle is entered by the Southern California batholith (VI), but also includes part of an area rated at VIII associated with the faults active in 1892 and 1956.

3. 116°-117° W. In California, Southern California batholith, rated VI (but rating as high as IX may apply to settled areas in alluviated valleys; see remarks under "Procedure and General Considerations"). At east margin, small part of Imperial Valley (IX). In Mexico, area assigned VIII (see A 2) with adjacent strip of VII (see A 4).
4. 117°-118° W. Vicinity of San Diego. Assigned VIII for the low sandy area on which much of the city, including the business center and harbor area, is situated; VII for a narrow strip, chiefly Tertiary, adjacent to the east; VI for the batholith area, as in A 3.
5. 118°-119° W. San Clemente Island. Chiefly Tertiary volcanics; assigned VII, although higher rating might be justified by proximity of the active fault zone passing along the east coast. Construction engineers here should carefully consider the degree of consolidation of foundation.

B. 33°-34° N:

1. 114°-115° W. VIII. The southwestern part of this area of desert mountains is within range of damage (on average ground) from earthquakes in the Imperial Valley area. The rest is in the area approaching the Colorado Plateau, the margin of which is a suspected source of large earthquakes. There are no data for outlining an area of VII in the intermediate space; since any settlement or construction is likely to be on alluvial foundation close to water supply, the higher rating is retained.
2. 115°-116° W. IX is assigned to the included areas of the Imperial and Coachella valleys, on the basis of historical records and many instrumentally located epicenters. The adjacent area to the northeast is assigned VIII on the probability of strong shaking from some of the same sources. VIII is extended northeast for reasons noted under B 1, and northwest to the base of the Little San Bernardino Mountains because of frequent earthquakes originating in that area, including some of magnitude 5 or over. The mountains occupying the northwest corner of the quadrangle are a fairly continuous, though fractured, igneous and metamorphic mass; they are assigned VI, together with a small projection of the Southern California batholith at the southwest.
3. 116°-117° W. Small to moderate earthquakes are more frequent in this quadrangle than anywhere else in southern California. The figure shows the zones of the active Elsinore, Agua Caliente, San Jacinto, and Mission Creek faults. Ratings are: IX for alluviated areas in San

Gorgonio Pass and Coachella Valley, VIII for a badlands area of Tertiary sediments adjacent to the San Jacinto fault on the northeast, VII for the hilly area between the Mission Creek fault and San Gorgonio Pass, and VI for the rocks of the Southern California batholith.

In the batholith area the discussion of small alluviated valleys under "Procedure and General Considerations" applies. Some of the alluviated area falls in the fault zones; there the risk is high and of special character. On a large-scale microregionalization map it might be appropriate to draw narrow bands of VII on the elevated batholith areas adjacent to the fault zones; the width to be assigned such bands would be difficult to determine. Palomar Mountain, with its observatory, is on the relatively narrow block between the San Jacinto and Agua Caliente faults; but it is doubtful whether as much as VII should be expected there on sound rock. Structures in the small alluviated areas on the mountain summit are subject to VIII, possibly to IX.

On the west edge of the quadrangle there is a small projection of an area of IX discussed under B 4.

4. 117°-118° W. A narrow strip on the west margin of this quadrangle is included in the area mapped for microregionalization in figure 2.

IX is indicated for alluviated areas. In the Pomona-San Bernardino valley, the southern part of which is on this quadrangle, indication of frequent occurrence has been added; this area is close to the very active San Jacinto fault zone, and at close range for a major earthquake on the San Andreas fault, as well as being near an east-west fault zone at the foot of the mountains north of it. Part of the Los Angeles Basin alluvium appears. At the east is a large alluviated area, which includes most of the Perris peneplain, with enclaves rated at VI, representing hills of igneous rock (the complicated situation is shown only roughly on this small scale).

VIII is assigned to the badland area noted on B 3.

VII is shown for Tertiary rocks, in the Santa Ana Mountains and extending down the coast. (Patches of Mesozoic rated at VI in figure 2 are not shown here.)

VI applies to igneous rocks of the Southern California batholith, including the Box Springs group between Riverside and the Perris peneplain, as well as the monadnock group of the Lakeview mountains.

5. 118°-119° W. The land area of this quadrangle is included in figure 2, except for Santa Catalina Island and the north tip of San Clemente Island (see A 5), both rated as VII as largely Tertiary. Part of Santa Catalina Island is Mesozoic; the rocks are probably Franciscan in age and character, and VII has been retained for them as for the northern Franciscan region.

The Inglewood fault zone has been indicated; this is a zone of somewhat special risk, particularly in connection with subterranean slippage, although no attempt has been made to show this in figure 2. It would have been justifiable to indicate the Norwalk fault zone in the same way, but the evidence is less satisfactory. In both zones the departure from normal risk, so far as surface construction is concerned, is mainly that usual for exceptionally unconsolidated ground.

Except for omission of small detail, the remainder of the mapping here follows figure 2.

6. 119°-120° W. Land areas are San Nicolas Island, rated VIII as prevalingly Quaternary, and the southern half of Santa Cruz Island, assigned VII as for Tertiary sediments.
7. 120°-121° W. This includes most of Santa Rosa Island, rated as VII like Santa Cruz Island.

C. 34°-35° N:

1. 114°-115° W. Assigned VIII, both in Arizona and California; see discussion for B 1.
2. 115°-116° W. Divided between VIII to the east and VII to the west by a very arbitrary line. In spite of the presence of active faults, a large part of the east-central Mojave Desert has been rated at VII instead of VIII. This expresses increased distance from the probable major earthquake sources in the Basin and Range province and near the west margin of the Colorado Plateau, without close approach to the San Andreas and Garlock fault zones, and with a higher ratio of igneous and other consolidated terrain to alluvial and fan cover than farther west.

In the southwest corner is a small part of the Little San Bernardino Mountains, rated VI.

3. 116°–117° W. The central part is rated VII. Isolated spots of alluvium here should rate at least VIII, as discussed for C 2. The northwestern part, including low ground near the Mojave River, as well as the epicenter of the Manix earthquake of 1947, is rated VIII. At the south the igneous mass of the San Bernardino and Little San Bernardino Mountains is assigned VI. Here microregionalization would assign higher rating to the alluvial and unconsolidated foundation surrounding Big Bear Lake in a populous resort area. The San Andreas and Mission Creek fault zones cross the southwest corner of the quadrangle.
4. 117°–118° W.

IX is assigned to the San Gabriel Valley alluvium, to the Pomona–San Bernardino valley, and to the Cajon Pass depression between the San Jacinto and San Andreas faults. To the north the Mojave Desert area is divided between VIII and VII as discussed under C 2.

VII is assigned to the northern extension of the Santa Ana Mountains, separating the San Gabriel and Pomona valleys. This generalizes out much detail (see fig. 2).

VII also is shown for an arbitrarily drawn narrow strip adjacent to the San Jacinto fault, on the southwest side.

VI is assigned to the igneous masses of the San Gabriel and San Bernardino mountains.

5. 118°–119° W. This is a complex area, mapped relatively in detail. Assignments are as follows:
IX—Alluvium of the Los Angeles Basin, of the San Fernando Valley, and of the eastern part of the Santa Clara Valley. Strips in the Mojave Desert adjacent to the San Andreas and Garlock faults.

VIII—Quaternary terraces from Santa Monica to Pasadena (not showing patches of alluvium); Quaternary and Tertiary rocks in a nearly north–south belt close to the Ridge Route highway; at the northwest, a small part of the complex north of the San Andreas fault (see C 3).

The western triangle of the Mojave Desert area is also rated VIII, except for the narrow strips of IX following the San Andreas and Garlock faults.

VII—An arbitrarily wide band in the San Gabriel Mountains adjacent to the San Jacinto and San Andreas faults, interrupted by the Ridge Route band of VIII.

The Tehachapi Mountains, and the igneous complex southwest of them, north of the Garlock and San Andreas faults.

Rocks of varying age and character, mostly Tertiary but including Mesozoic and variously dated igneous masses, in the Santa Monica Mountains, between the San Gabriel Mountains and the San Fernando Valley, and west of the Ridge Route.

VI—The principal igneous mass of the San Gabriel Mountains; also igneous rocks west of the Ridge Route and south of the arbitrary limit of VII.

6. 119°–120° W. Rating in this and in C 7 is affected by a large uncertain factor, since we do not know the source of the major earthquake of December 21, 1812. The alluviated area of the Santa Clara Valley and the Ventura Basin is rated IX with confidence; towns there repeatedly report stronger shaking than other points at the same distance from the epicenters of the earthquakes concerned. The patch of IX near the north edge of the quadrangle is the Cuyama Valley. Just north of it is a small area of hills rated VIII. VIII is also assigned to an area at the northeast, including hills immediately north of the San Andreas fault and extending north to include Wheeler Ridge; east of this is a small part of the area of VII associated with the Tehachapi Mountains (C 5, D 5). At the northeast corner is the epicenter of the 1952 earthquake.

VIII is applied to the terrace area along the coast including Santa Barbara, where there has been damage at or near that level on several occasions (including June 29, 1925).

VII is assigned to the better rock in the hill and mountain areas, chiefly Tertiary with some Mesozoic; but the igneous masses of Mount Pinos and Frazier Mountain are included in the band of VII adjacent to San Andreas fault, while similar rocks immediately to the south are rated at VI.

VII is also assigned to Santa Cruz Island, where Tertiary ground prevails.

Zones of probably special risk, besides that of the San Andreas fault, are those of the Santa Ynez fault running east–west near the center of the quadrangle, and the somewhat uncertainly evaluated Nacimiento fault entering from the northwest.

7. 120°–121° W. IX applies to the alluviated valleys of the Santa Maria and Santa Ynez rivers, and to patches of sand dunes on the coast. VIII is assigned to Quaternary terraces, including those of San Miguel Island. VII is assigned to the hill areas, which are Tertiary with some Mesozoic, and to the prevailingly Tertiary Santa Rosa Island.
- D. 35°–36° N:
1. 114°–115° W. In California this includes only a small triangular desert area, falling within the area of VIII as discussed under B 1.
 2. 115°–116° W. Included in the general Mojave Desert area assigned VII; see C 2. Areas of alluvium probably should be rated VIII.
 3. 116°–117° W. This includes the eastern end of the Garlock fault zone. Assignments are:
 IX—Strip adjacent to the Garlock fault on the south. Area of prevailing alluvium spreading south to the Garlock fault from Death Valley. Alluvium in the Amargosa drainage.
 VIII—Western part of the Mojave Desert area (see C 2), with projection eastward south of the Garlock fault and strip of IX. Small mountainous area just north of the Garlock fault and west of Death Valley.
 VII—Eastern part of Mojave Desert area. Mountains west of Death Valley and north of the area assigned VIII.
 4. 117°–118° W. Crossed by the Garlock fault zone.
 IX—Strip along Garlock fault on the south. North of it, large alluviated area of the southern Owens Valley and Searles Lake Basin. Southern part of Panamint Valley with patch of deep alluvium in its southern extension, near Wingate Pass.
 VIII—North part of western Mojave Desert area. Patch of mountains adjacent to Garlock fault on north, near Wingate Pass; includes igneous rocks and ancient sediments.
 VII—Mountainous areas, including the Argus and Panamint mountains. Largely igneous and Paleozoic, but rated at this level because of numerous active faults near or cutting through the mountains. At the west appears the eastern margin of the Sierra Nevada, also assigned VII.
 5. 118°–119° W. Garlock and White Wolf fault zones indicated.
 IX—Strip of the Mojave Desert adjacent to the Garlock fault. Alluvium of the eastern San Joaquin Valley and the west edge of Owens Valley. Alluvial basins internal to the Tehachapi Mountains: Tehachapi-Cummings Valley, Walker Basin, Kelso Valley, South Fork Valley (and others not shown); these are important as sites for towns and cultivation.
 VIII—At the southeast, a small triangle of the Mojave Desert area. At the west, Quaternary terraces northeast of Bakersfield, separated from the Sierra batholith by a fault.
 VII—Most of the Tehachapi Mountains, excluding alluvial basins. An arbitrarily bounded band of the eastern Sierra Nevada adjacent to Owens Valley, widened northward to include the Walker Pass area (see also E 5).
 VI—Igneous and metamorphic rocks of the Sierra Nevada batholith, excluding the eastern band of VII.
 6. 119°–120° W. San Andreas fault zone shown.
 IX—Alluvium of southern San Joaquin Valley, except as noted under VIII. Alluvium of the Carrizo Plain, southwest of the San Andreas fault.
 VIII—South end of central band in San Joaquin Valley, speculatively assigned this intensity; see discussion for E 6. Quaternary terraces on east and west sides of the valley. Tertiary and older rocks adjacent to the San Andreas fault, rated at this level because of proximity and extensive fracturing.
 VII—Southwest corner, part of the general Coast Range area of this rating; compare C 6 and D 7.
 7. 120°–121° W.
 Fault zones: San Andreas, Nacimiento.
 IX—Alluvium, at edges of quadrangle. South, Santa Maria Valley; east, Carrizo Plain; north, southern Salinas Valley.
 VIII—Quaternary terrace areas, the largest west of the San Andreas fault. Small coastal area north of Santa Maria Valley. Small areas east of the San Andreas fault in the northeast corner and on the east margin. Tertiary area adjoining the San Andreas fault on the southwest, between it and the Quaternary terraces.

VII—Prevailingly Tertiary. San Luis Range near the coast. Areas on both sides of the Nacimiento fault zone, and at north on northeast side of the San Andreas fault, where Cretaceous is exposed.

VI—Franciscan area southwest of Nacimiento fault, extending as a belt southeast to near San Luis Obispo. It is possible this should be included in VII, as for most other Franciscan areas. Granitic area in the La Panza Range, west of the north end of the Carizzo Plain.

8. 121°–122° W.

Nacimiento fault zone shown.

VII—Northeast of the fault, Tertiary and Cretaceous.

VI—Southwest of the fault; Franciscan. Possibly should be rated VII; compare D 7.

E 36°–37° N:

2. 115°–116° W.

In California, a very small triangular area, rated VII. The adjacent Nevada area is mostly assigned VIII (fig. 4).

3. 116°–117° W.

IX—Alluviated areas of Death Valley and the Amargosa drainage.

VII—Remainder of the quadrangle, chiefly mountainous.

4. 117°–118° W.

Fault zone: south end of Owens Valley. See E 5.

IX—Alluvium; Owens Valley, Panamint Valley, northern Death Valley.

VII—Remainder of the quadrangle; chiefly mountainous, including igneous rocks and Paleozoic sediments, in part incompletely mapped and studied.

5. 118°–119° W.

Fault zone: Owens Valley, associated with the 1872 earthquake.

IX—Alluvium of Owens Valley. In this quadrangle, but too narrow to indicate within the Sierra Nevada igneous area, is the alluviated canyon of the South Fork of the Kings River, now developing as a camp ground and resort, where rating of at least VIII and possibly IX, would be appropriate.

VI—Sierra Nevada batholith, except for the Kings River Canyon and still smaller similar areas.

6. 119°–120° W.

IX—Alluvium of the San Joaquin Valley, except as noted in the next paragraph.

VIII—In the central part of the San Joaquin Valley, along the east bank of the San Joaquin River, a narrow band of VIII has been drawn for purely theoretical reasons. The writer believes that seismic waves entering the valley either from east or from west will be partly absorbed before reaching its center surface. No earthquakes are known to originate under the valley proper, and hence slightly lower maximum intensity is to be expected along a central band; however, it is uncertain whether this hypothetical band is correctly placed as shown.

VIII is also applied to Quaternary terraces at the base of the Sierra Nevada between the San Joaquin and Kaweah rivers.

VI—Western edge of the Sierra Nevada batholith.

7. 120°–121° W.

Fault zone: San Andreas.

IX—Alluvium of San Joaquin Valley, except for the hypothetical central band of VIII (see E 6). Part of Salinas Valley in southwest corner.

VIII—Central band of San Joaquin Valley; see E 6. Tertiary, adjacent to San Andreas fault on both sides, and Quaternary terraces east of it (including the Buena Vista Hills area).

VII—At the south edge, small part of Cretaceous area between the San Andreas fault and younger rocks on the east. Large Franciscan area, extending from the northwest to near the center (vicinity of Coalinga). In southwest corner, small part of western Franciscan area. On west margin, southeast end of prevailingly granitic area adjacent to San Andreas fault (see E 8).

8. 121°–122° W.

Fault zone: San Andreas.

IX—Alluvium of Salinas Valley and Hollister area.

VIII—Tertiary adjacent to San Andreas fault on both sides. Coastal hills near Santa Cruz.

VII—Jurassic and Cretaceous, including Franciscan, in northeast and southeast corners. Granitic and other rocks adjacent to the San Andreas fault on the southwest side, roughly from San Juan to Soledad.

VI—Generally granitic area southeast of and near Monterey. This is far enough from the San Andreas fault to be assigned so low a rating; but it is near the Nacimiento fault, and more accurate information on the latter might raise the rating to VII.

F. 37°–38° N:

4. 117°–118° W.

The triangular corner in California is part of a largely mountain area assigned VII, except that the large depression of Eureka Valley is assigned VIII.

5. 118°–119° W.

The northern part of the fault zone of the 1872 earthquake is shown.

IX—Alluvium: northern Owens Valley; Long Valley (east of Mammoth); Adobe Meadows (near the north edge); and an area in the northwest corner, southeast of Mono Lake.

VIII—A heterogeneous area including alluvium, volcanics, and miscellaneous rocks, between Bishop and Mono Lake east of the Sierra Nevada.

VII—Sierra front, east of the crest and west of Owens Valley; also mountains east of Owens Valley.

VI—Principal Sierra Nevada batholithic area, in southwest quarter of the quadrangle.

6. 119°–120° W.

IX—Alluvium, in southwest corner (San Joaquin Valley) and in northeast corner (Mono Lake Valley).

VII—At the northeast, Sierra Nevada east front and foothill area, with heterogeneous fractured rocks, Tertiary and later.

VI—Sierra Nevada batholith, covering most of the quadrangle. This includes the alluviated resort area of Yosemite Valley, too small to show, which should be rated IX, except at its margins on consolidated ground.

7. 120°–121° W.

IX—Alluvium of San Joaquin Valley, except as noted below.

VIII—Northern end of hypothetical central band of San Joaquin valley (see E 6); Sierra Nevada foothill area, with Tertiary volcanics and some Quaternary terraces.

VI—Sierra Nevada batholith.

8. 121°–122° W.

Fault zones: San Andreas, Haywards, Calaveras.

IX—Alluvium. San Joaquin Valley; Santa Clara Valley; vicinity of Pleasanton and Livermore.

VIII—Between Haywards and Calaveras faults, and between Haywards fault and San Joaquin Valley, north of the Pleasanton area. Tertiary generally, but including Cretaceous rated VIII because of fault proximity. Also Quaternary terraces (Sierra Nevada foothill area) in northeast corner.

VII—Jurassic and Cretaceous. Mount Diablo and southeastward along the edge of the San Joaquin Valley; Franciscan area including Mount Mocho and Mount Hamilton.

9. 122°–123° W.

This quadrangle includes San Francisco. Fault zones: San Andreas, Haywards, Calaveras.

IX—Alluvial and tide-flat areas adjacent to San Francisco Bay, extending southeastward toward Santa Clara Valley. Within the city IX includes artificial fill which was the area of principal earthquake damage in 1906.

VIII—Remainder of the quadrangle, except as noted for VII. Chiefly Tertiary with some Mesozoic sediments and some granite. Local effect of better ground largely compensated by proximity to the San Andreas fault. On a large-scale map some small spots might be assigned VII, but a number of small alluviated spots should then be rated IX.

VII—Granodioritic rock in the Santa Cruz Mountains.

G. 38°–39° N:

5. 118°–119° W.

In California, only a triangular area in the southwest corner. Mostly rated IX, for alluvium of Mono Valley. Small areas assigned VIII and VII at north and east points of the triangle (see G 6 and F 5).

6. 119°–120° W.

IX—Alluvium of Mono Valley in southeast corner.

VIII—Alluviated area about Bridgeport, generally better ground than the above.

VII—Hilly area of heterogeneous geology east of the main Sierra Nevada.

VI—Sierra batholith, western part of the quadrangle.

7. 120°–121° W.

VIII—Sierra Nevada foothill area, in southwest corner.

VI—Remainder of quadrangle, chiefly Sierra Nevada batholith rocks, but with some volcanics and alluvium.

8. 121°–122° W.

IX—Alluvium of Sacramento Valley.

VIII—Patch of Quaternary terraces west of Rio Vista; at the east, Quaternary terraces and Tertiary volcanics in the Sierra Nevada foothills.

VI—Sierra Nevada, in northeast corner.

9. 122°–123° W.

San Andreas fault zone crosses the southwest corner.

IX—Alluvium: adjacent to San Pablo Bay; Sacramento Valley; Cotati Valley (including Santa Rosa and Sebastopol); area south of Clear Lake.

VIII—Assigned to the remainder of the quadrangle south of a boundary drawn near 38° 30'. Largely Tertiary. Occurrences of better ground offset by proximity to the San Andreas fault at the southwest, and by history of shocks damaging at Vallejo, Napa, and in the Sacramento Valley.

VII—Assigned (except for areas of IX) north of the boundary near 38° 30', in mainly Franciscan terrain.

10. 123°–124° W.

San Andreas fault zone shown.

VIII—Rating for most of the area; Mesozoic, including Franciscan, adjacent to the fault.

VII—Northeast corner, assigned this lower rating because of increased distance from the San Andreas fault.

H 39°–40° N:

7. 120°–121° W.

VIII—Alluvium of Sierra Valley; not assigned IX because of distance from most probable sources of great earthquakes. Similar remarks apply to several areas in northeastern California.

VII—Sedimentary and volcanic terrain.

VI—Sierra Nevada.

8. 121°–122° W.

IX—Alluvium of Sacramento and Feather River valleys.

VIII—Sierra foothill terrace area, southward from Marysville.

VII—Sierra foothill area northward from Marysville. Also hilly area from Marysville Buttes northward.

VI—Sierra Nevada batholith.

The placing of the division between VII and VIII at Marysville is arbitrary; it represents decreasing general expectation of shaking northward and eastward.

9. 122°–123° W.

IX—Alluvium of Sacramento Valley.

VII—Mesozoic, west of Sacramento Valley, including Franciscan. Also Quaternary terraces, not rated VIII as in localities nearer major earthquake sources.

VI—Northwestern corner, in the area of the Klamath and Trinity crystalline rocks.

10. 123°-124° W.

This is part of the northern Franciscan area, assigned generally VII, with VIII in the southwest corner toward the San Andreas fault.

J. 40°-41° N:

7. 120°-121° W.

Although there are known earthquake origins in this area, as for the shock of January 30, 1885, alluvial areas are not graded IX since it is believed that this intensity would be reached only on small areas of the worst ground, not likely to be used for construction. Major earthquake sources are all at comparatively large distance.

VIII is assigned to the region about Honey Lake, to a marshy area in the north center, and to a small part of the Lava Beds appearing at the northeast corner (see K 7).

VII—Most of the remaining area, rock chiefly volcanic.

VI—Sierra Nevada rocks, in the southern part of the quadrangle.

8. 121°-122° W.

This is the area about Mount Lassen; rocks are chiefly volcanic. Assigned VII, except for VI for Sierra Nevada rocks in the southeast corner. This neglects the possibility of locally violent shocks of volcanic origin.

9. 122°-123° W.

IX—Two patches of alluvium in the northern Sacramento Valley, east of Red Bluff and near Anderson.

VII—Remaining rocks of the area, Tertiary with some Quaternary terraces, excluding the next:

VI—Crystalline rocks of the Klamath-Trinity region in the northwest part of the quadrangle.

10. 123°-124° W.

This includes most of Trinity County; the area is incompletely studied geologically.

VII—Southwestern part, in the generally Franciscan area.

VI—Northeastern part, including the Trinity Mountains, taken as part of the Klamath crystalline area.

11. 124°-125° W.

Shelter Cove fault zone shown.

IX—Coastal area of unconsolidated ground about Humboldt Bay.

VIII—Adjacent terraces.

VII—The remainder of the area, even in the vicinity of the fault zone. Chiefly Franciscan rock. Towns here have several times been damaged with intensity VIII; most of them are in the fault zone as shown, and the rest are in small alluviated areas.

K. 41°-42° N:

7. 120°-121° W.

IX—Assigned to the Goose Lake area because of very unstable ground, past history of local earthquakes, and approach to known or probable earthquake sources in Nevada.

VIII—Northeastern area, excluding the above-described area of IX. This is in the Lava Beds region.

VII—Remainder of the quadrangle.

8. 121°-122° W.

VIII—Lake-bed areas, which elsewhere would be assigned IX, as for Goose Lake in K 7.

VII—Volcanics covering most of the area.

VI—A small point of the Klamath crystalline complex, at the southwest.

9. 122°-123° w.

VIII—Alluvium of Shasta Valley (possible IX; see remarks for K 7 and K 8).

VII—Volcanics.

VI—Klamath crystallines, at west and south.

10. 123°-124° W.

VII—Small part of the Franciscan area, southwest corner.

VI—Generally. Klamath Mountains region, crystalline and metamorphic.

11. 124°–125° W.

Narrow strip of the north coast.

IX—Alluvium and terrace area near Crescent City. This is based on proximity to known high seismicity offshore, plus the fact of damage in 1873.

VII—Franciscan, to the south.

VI—Klamath crystallines.

UNITED STATES: GENERAL AND HISTORICAL

Regionalization problems in the United States outside California and western Nevada differ in many respects from those considered to this point. Geological, cultural, and historical circumstances vary extremely. This large and heterogeneous territory will here be designated as “the major area”; when necessary, “the minor area” will be used as including California and western Nevada.

Seismicity in the major area, as judged by the incidence of small to moderate earthquakes (magnitudes 3 to 6), is much lower than in the minor area. However, one or more great earthquakes of magnitude 8 or over are on record for the major area. Such events are occasional in time and sporadic in space. The consequent difficulty of estimating the probability of their causing strong shaking in the future, especially at locations which have not been thus affected in the last three centuries, constitutes the principal obstacle to definitive regionalization. As noted under “Procedure and General Considerations,” the geographical distribution of epicenters of small shocks is not a sure guide to the probable locations of great earthquakes.

Literature on earthquakes in the United States is voluminous and widely dispersed. Detailed publications describe only individual events, or the seismicity of states and smaller areas. Fortunately, the principal data, adequate for use in this connection, have been summarized in publications of the U. S. Coast and Geodetic Survey. For the major area, discussion with lists and a map was published by Heck (1938); a shorter but later summary for both major and minor areas was given by Neumann (1952). Many details, and later information, are to be found in the annual *United States Earthquakes*.

The following notes on earthquakes of special interest in regionalization are derived chiefly from Coast and Geodetic Survey publications.

1663, February 5. A great earthquake on the St. Lawrence rift; epicenter probably near the present site of Three Rivers, Quebec. Intensity VI–VII as far distant as Massachusetts Bay. This event, and the probability of similar occurrences elsewhere along the same structure, is the chief basis for the rating of IX in the adjacent region, partly supported by data for smaller earthquakes, as in 1925 and 1935.

1755, November 18. Intensity at least VIII in Massachusetts; felt over a wide area from Chesapeake Bay to Nova Scotia. This and smaller shocks elsewhere in New England justify retaining VIII for the entire coastal area.

1811–1812. Center in the region of New Madrid, Missouri. Three large shocks, on December 16, January 23, and February 7, of which at least the first and last were great earthquakes (probable magnitude 8 or over). Effects of great violence, and changes in terrain over the large central area. Shaking felt over more than half the present United States (excepting Alaska). The principal published description is that by Fuller (1912).

1843, January 4. Origin also in the region of New Madrid. Damage at Memphis (intensity VI to VII). Some chimneys fell at St. Louis and at Nashville. The earthquake was generally felt in South Carolina and into Georgia, but the area shaken was far smaller than in 1811–1812.

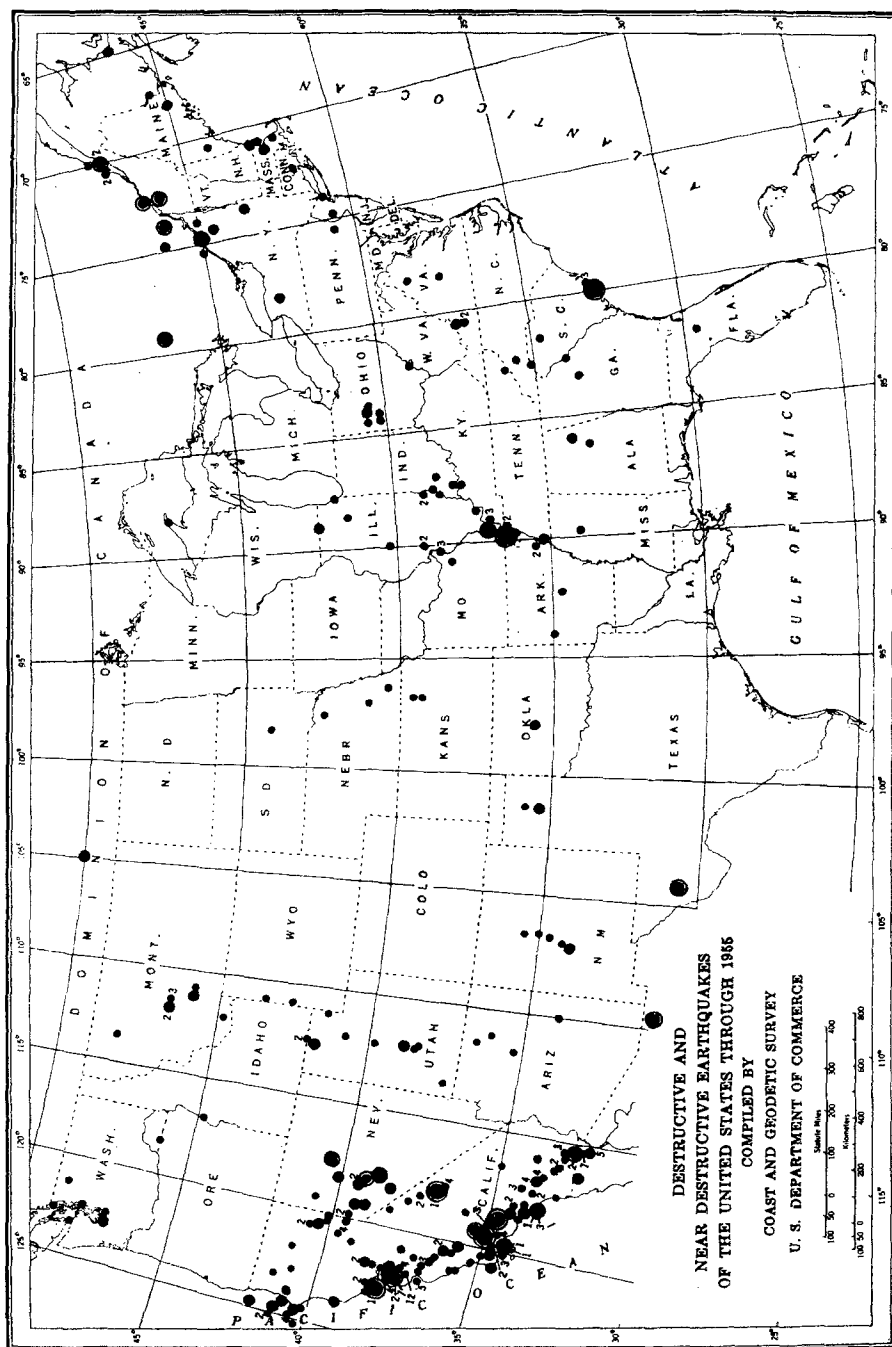


Fig. 7. Epicenters for destructive and near-destructive earthquakes of the United States through 1955 (U. S. Coast and Geodetic Survey, from *United States Earthquakes*, 1955).

1879, January 12. Northern and central Florida. Intensity at least VI at St. Augustine.

1884, August 10. Epicenter probably off the coast not far from New York City. Walls cracked on Long Island. Felt from Connecticut to Pennsylvania.

1886, August 31. The well-known earthquake near Charleston, South Carolina, reported in detail by Dutton (1889). Intensity at Charleston about VIII on the better ground, IX on less stable foundation; extensive damage and loss of about 60 lives. Weak chimneys fell (VI-VII) as far as 100 miles from Charleston. Felt to distances of 800 miles.

1887, May 3. Major earthquake with surface faulting, in Sonora, Mexico, just south of the international boundary. Most severe damage, and some loss of life, at Bavispe, Sonora. Widely felt in New Mexico, Arizona, and Texas.

1895, October 31. Intensity IX near Charleston in southeastern Missouri. Damage at points as distant as Cairo, Illinois. Shaking felt over a very large area extending from Canada to Mississippi and Louisiana, and from Georgia and Virginia to Kansas and South Dakota.

1906, July 16. Strongest of a series of damaging shocks centered near Socorro, New Mexico. Felt to distances of over 200 miles.

1915, October 2. Major earthquake (magnitude 7.6) with faulting in Pleasant Valley, south of Winnemucca, Nevada. (Jones, 1915.)

1925, February 28. Earthquake on the St. Lawrence rift; magnitude 7. Felt over a wide area extending far into the United States; damage only in Canada. Depth of origin possibly greater than for average shallow earthquakes.

1925, June 27. Montana. Magnitude $6\frac{3}{4}$. Maximum intensity IX.

1925, July 30. Panhandle area, north Texas. (Pratt, 1926.)

1929, August 12. Damaging (VII) especially at Attica, New York. Intensity about VI at Niagara Falls. Felt over a wide area extending into New England and northeastern Ohio.

1931, August 16. Magnitude 6.4. Epicenter in western Texas; much damage (VII) at Valentine. Felt over an area estimated at 450,000 square miles.

1932, December 20. Magnitude 7.3. West-central Nevada, in a nearly uninhabited area near the south end of the belt mapped as of intensity IX, which was approximately the observed maximum. Felt to considerable distances, including San Francisco and Los Angeles. Described by Gianella and Callaghan (1934).

1934, March 12. Magnitude 6.6. Epicenter near Kosmo, at the north end of Great Salt Lake, where there was much cracking of the ground which may possibly have represented faulting. Minor damage over a large area, including Salt Lake City.

1935, October 18 and October 31. Magnitudes about $6\frac{1}{4}$. Shocks very damaging at Helena, Montana; intensities probably not over VIII. Felt over wide areas. (Ulrich, 1936.)

1935, October 31. Also of magnitude $6\frac{1}{4}$. Epicenter in the Timiskaming region, Canada, north of the St. Lawrence rift. Source under the Canadian Shield, probably deeper than average. Felt to long distances; minor damage at Cortland, New York.

1937, March 2 and 9. Shocks damaging in west-central Ohio, chiefly at Anna and Sidney, where chimneys fell. Plaster cracked as far away as Fort Wayne and Indianapolis, Indiana.

1940, December 20. Magnitude 6. Damaging in a small area in New Hampshire. Felt generally in New England, New York, and New Jersey.

1944, July 12. Magnitude 6.1. Central Idaho. Intensity VI-VII (rockfalls reported in the mountainous area near Seafoam, Idaho.) Although the instrumental record shows this was one of the largest of Idaho earthquakes, it attracted relatively little attention. The epicenter is within the area of the Idaho batholith, generally mountainous and thinly populated. The only damage reported was the fall of two chimneys at Cascade in a narrow alluviated valley. The shock was felt over most of Idaho and into adjacent states.

1949, April 13. Magnitude 7. Epicenter in the Puget Sound area; extensive damage (VIII) at Seattle, Olympia, etc.

1952, April 9. Oklahoma; magnitude 5.5. Discussed in the next section.

1953, December 15. A small earthquake, of interest as having reached intensity VI in the vicinity of Portland, Oregon.

1954, December 16. Magnitude 7.1. Western Nevada, in the center of the belt of IX indicated in figure 3, in a nearly uninhabited region. Spectacular faulting; perceptibility extended far into adjacent states. Described by Tocher *et al.* (1957).

UNITED STATES: DETAILS

Figure 4 shows fewer and wider zones for the major area than for California. This is in part due to procedure; if regionalization maps were first drawn up for each state on a large scale, and then generalized, more small details would appear on the resulting map. However, the generally lower seismicity of the major area, and the uneven distribution of recording seismological stations, would make detailed local regionalization more speculative than in California.

Moreover, a real difference exists. At many points in the major area earthquakes have occurred which reached maximum intensity of VIII or less, even when the epicenter was in a settled district, and yet have been felt over very wide regions. An example is the Missouri earthquake of 1895. This and other instances were discussed by Gutenberg and Richter (1942), in terms of a depth of origin greater than that usual in California, though by no means in the category of deep-focus earthquakes.

A later instance is the earthquake of April 9, 1952 (*United States Earthquakes*, 1952, pp. 6-9; Miller, 1956). This shock attained maximum intensity of VII over a small area in Oklahoma, including El Reno, Oklahoma City, and Ponca City; yet it was felt in some directions to distances of nearly 500 miles (in Iowa especially). This earthquake had a magnitude of about 5.5. An earthquake of magnitude 6.5 from the same source might be expected to attain maximum intensity X, and intensity VII should extend to about the same distance as IV in the 1952 shock (about 250 miles).

The reader should be reminded at this point that the areas assigned higher intensity do not necessarily represent the location of earthquake epicenters, but merely the probability of strong shaking from sources possibly at considerable distance.

Geographical arrangement and order of material in this section follows Heck (1938) and Neumann (1952). The same subdivisions are regularly used in the series *United States Earthquakes*.

Northeastern region (New England and New York).—Regionalization here depends critically on judgment regarding the probable effects of earthquakes along the St. Lawrence rift zone. The "Seismic Probability Map" of 1948 assigns its highest rating to a narrow zone in the United States paralleling the St. Lawrence; the obviously arbitrary boundary is a straight line. The map for Canada by Hodgson (1956) shows the same high rating extending northward to much greater distance; this agrees approximately with the boundary in figure 4 between IX and VIII. In the United States our figure shows the corresponding boundary curved to take in a slightly larger area of central New York; this has the effect of running the boundary through the Adirondack area, where there is a history of small local earthquakes. Although the general ground in that area is undoubtedly sound enough to warrant lower rating, works of construction are likely to be founded on local patches of alluvium.

In Canada bands of VIII and VII have been drawn, rather to indicate rough probabilities than as actual regionalization, and in order to provide transition to the solid basement rock of the Canadian Shield, assigned a maximum not over V. The boundary between VIII and IX crossing from Lake Ontario to Lake Huron is close to that drawn by Hodgson.

The coastward part of the northeastern region has been assigned VIII without distinction. Here microregionalization would show many local differences, and the history of earthquakes originating near or off the coast would require close study. Small shocks are known to have originated on land near the coast from New Jersey to Maine.

Eastern region (from Pennsylvania and New Jersey south to Florida, thence west to Tennessee and Mississippi).—IX is assigned to a belt 100 miles wide or more, whose center line extends from

the vicinity of New Madrid, Missouri, to that of Charleston, South Carolina. This is based primarily on the occurrences of 1811–1812 and 1886. Of themselves, these do not justify a continuous belt, and most authorities would give the intermediate part of the belt shown a lower rating. The southern boundary of the continuous belt here mapped is drawn to include the probable epicenters of known earthquakes in northern Mississippi, Alabama, and Georgia. Small earthquakes are reported rather commonly in eastern Tennessee. Combining these data, the writer feels that a rating of IX is applicable in the whole of Tennessee to structures on fair to poor ground, which is that occupied by most of the towns and settled areas.

Broad bands of VIII are drawn paralleling the band of IX. In addition, VIII is extended northeastward through the Virginias and Pennsylvania, along the Appalachian structures, where minor shocks are relatively frequent. In spite of locally poor ground, the area including southeastern Virginia and northeastern North Carolina has been left at VII. Similarly, VII has been allowed to stand for the Gulf coast area south of the band of VIII; this rating of VII has been extended into northern Florida, with consideration of the earthquake of 1879. Southern Florida, being more remote, has been rated at VI; although the large earthquakes of the West Indies are sometimes perceptible at this distance, higher intensity than VI from that source is unlikely.

Central region.—Regionalization in this area depends to a great extent on its relation to the Canadian Shield, the St. Lawrence rift, and the origins of the earthquakes of 1811–1812.

Maps in the U. S. Coast and Geodetic Survey publications cited show epicenters which readily suggest to the eye an active alignment in prolongation of the trend of the St. Lawrence rift, through Lakes Ontario and Erie and thence across Ohio and Indiana to southeastern Missouri. This has lately been emphasized by Wilson and O'Halloran (1958). If this evidence were accepted for regionalization, it would be represented in figure 4 by comparatively small changes; it would only be necessary to replace VII by VIII in central Indiana and immediately adjacent areas. It would probably be exaggeration, on present evidence, to extend the belt of IX along the alignment and raise adjacent areas to VIII.

There is no known structural interpretation for this alignment—an objection which is not decisive, since a young active structure, along which earthquakes originate at depths of the order of 15 miles, need not be evident at or near the surface. However, the appearance of alignment depends on clusters of small earthquakes affecting southwest Indiana and west-central Ohio. The history of the Ohio shocks suggests that they represent one of many regions of local instability with relatively frequent small earthquakes, and do not indicate a major structure. They are classifiable as part of the marginal seismicity surrounding the Canadian Shield.

Stable shields in other continents are usually fringed by belts of moderate seismicity, with occasionally large earthquakes. This is the reason for the belt of VIII shown south of the Great Lakes and trending northwest into Canada. Such fringing belts often include downwarped or downfaulted depressions, as in central Asia and central Australia; hence the belt of VIII has been drawn through the Lake of the Woods and Lake Winnipeg, thence to trend northwest toward Great Slave Lake. This northwestern belt is highly speculative, and unsupported by known earthquake data.

IX has been drawn to surround the 1811–1812 epicenters in the region of New Madrid, Missouri, with extension westward to consider strong shaking from that and other sources. Adjacent bands of VIII are drawn; this leaves a narrow band of VII crossing Illinois, Indiana, and Ohio.

VII is shown for the Gulf Coast area of Texas and Louisiana. Although the ground here is generally more unstable than farther north, the distance from known or probable earthquake sources requires a slightly lowered rating. The large area rated at VII in the north, including most of Nebraska and the Dakotas, might be subdivided or modified with better information. Population there is generally sparse, present reporting is incomplete, historical data are fragmentary, and there are no local seismological stations.

Western mountain region.—Occurrence of several known and locally damaging earthquakes in Oklahoma and the northern Panhandle of Texas supports inclusion of those areas under VIII.

A band of IX is drawn to include the epicenters of central New Mexico (notably those near Socorro) and that of 1931 in western Texas.

A long band of IX is shown crossing the United States from north to south, through Montana, Idaho, Utah, and Arizona. At the north this follows the eastern front of the Rocky Mountains, including the epicenters of the damaging Montana earthquakes of 1925 and 1935. Southward it

follows the eastern margin of the Great Basin, in the vicinity of the Wasatch fault and others, with known minor to moderate earthquakes. Still further south it follows the boundary of the Colorado Plateau; this is unsupported by direct evidence. Minor earthquakes are known a little farther east, within the Plateau area; but on account of relatively good ground the rating there has been retained at VIII. The reason for assigning potential rare origin of strong earthquakes to the Plateau boundary is much like that for the boundary of the Canadian shield; it is an example of what the Soviet workers term "contrast." Southeastward this same belt of IX includes the source of the major Sonora earthquake of 1887.

VIII is indicated adjacent to this belt of IX, eastward and in part also to the west; the latter includes the Basin and Range area, chiefly in eastern Nevada.

Generally better ground in a prevailingly mountainous area results in assigning VII to western Montana and most of northern Idaho. The Idaho batholith is rated as VI, although at least one strong earthquake (that of 1944) originated within it.

Washington and Oregon.—The trough including Puget Sound and the Willamette Valley is rated VIII; the area had a history of small earthquakes before the locally destructive shock of 1949. In many coastal localities ground is exceptionally unstable; in microregionalization these would be mapped as IX. VIII is shown for unstable ground in the vicinity of Klamath and Goose lakes in southern Oregon.

VI is assigned to the crystalline rocks of the Klamath group extending north from California into Oregon; to the central mass of the Olympic Mountains; and to the large northern batholithic area extending into Canada.

The remainder of the area is rated VII.

A well-known alignment of epicenters extends southeastward across central Washington into Oregon; but the associated activity does not appear high enough to raise the rating above VII for ordinary ground.

California and western Nevada.—This, which we have called the minor area, accounts for most of the seismicity of the United States. California has been mapped in detail in figure 3; comparison will show the effect of small-scale generalization. The fault zones have been omitted in figure 4. In Baja California the patch of VIII is that noted previously as associated with the earthquakes of 1892 and 1956, among others.

The general rating of VIII for Nevada is broken by a band of IX representing the earthquakes of 1915, 1932, and 1954. Here again we have an alignment not correlated with known structures, but it obviously has some tectonic significance. Prolonged southwest, this band would approach the area of the 1872 Owens Valley earthquake; if the association were accepted as real, it would lead to far-reaching modification of regionalization in the intervening parts of Nevada and California.

REMARKS ON THE UNITED STATES MAP

In making use of figure 4, it should be taken as representing long-term risk to be considered for structures intended to be permanent, or in long-term planning such as developing new townsites or industrial centers. An individual structure intended for a life of the order of thirty years might within that life be exposed to shaking of no more than one scale degree below that mapped. However, in setting insurance rates, it must be considered that in a given area there may be many weak structures which when insured together will constitute a major risk. Thus the minor earthquake of March 22, 1957, originating at the edge of the San Francisco metropolitan area, caused total damage well in excess of half a million dollars, which was the sum of many individual small items.

Probable intensity VII is mapped for many areas which it is customary to consider nonseismic with the result that it is publicly stated that there is "no earthquake risk." If the map were made the basis of regulation, it should occasion no hardship in connection with proper construction. Structures showing any but the most minor damage when subjected to intensity VII simply are not well built, and

should not be constructed under any respectable system of building regulations. Weak construction is not safe under ordinary conditions of use, and with the lapse of time often becomes further weakened to the point of collapse. Major earthquake disasters, such as that in the Long Beach area in 1933, have often been precipitated by the simultaneous failure of numerous such structures under comparatively moderate shaking.

The three most doubtful indications in figure 4, which the writer would be most ready to change on revision in the light of further evidence, are:

1. The entirely hypothetical band of VIII extending northward into Canada along the west margin of the Canadian Shield.

2. Assignment of maximum IX to a belt including Charleston, South Carolina, and extending westward. There is no doubt about the assignment of IX to the western end of this belt, which includes the New Madrid region.

3. Neglect of the apparent active alignment extending from Lake Erie southwest across Ohio and Indiana to the New Madrid region.

The confidence with which lines are drawn in figure 4 differs widely from region to region, because of the extreme variations in population density, completeness of historical data, geological mapping, and geophysical data including seismograph registration.

The precise drawing of lines is largely a matter of guesswork, except when separating areas of different ground, such as rock and alluvium. The writer earnestly hopes that no one will go to the length of enlarging the map and using it to assign different risk values to towns on the same type of ground five miles apart, simply because on the enlarged scale the line appears to pass between.

CITY AREAS

Regionalization of a large city presents special problems, which depend in close detail on the character of the ground. Where there are appreciable differences of level, the hilly and elevated areas, for which earthquake risk is generally less, are normally occupied by residences and small business. The principal business and industrial centers, and of course harbor development, are usually on lower ground, which may be sandy, alluvial, or even marshy. This lower ground is often also occupied by dilapidated residential sections, with numerous old structures which are fire and disease traps as well as earthquake risks.

Local spots of artificial fill, replacing old ponds or rubbish pits, or originating in grading uneven ground, are danger areas difficult to detect without careful study of old records.

Cities specifically commented on here are among those with whose sites the writer has some personal acquaintance, or for which he has had usable documents available, or where the geographical situation calls for special comment. The selection is thus rather arbitrary, and no inference of any kind should be drawn because some city or town is included in or excluded from the list.

NORTHEASTERN REGION

Boston is a good example of the effect of different level and character of ground. The earthquake of 1755, and other minor events, leave no doubt that VII is to be expected here even on fairly good ground. Whether the Palaeozoic sediments on hill ground are sufficiently consolidated to grade down to VI would be difficult to decide on the spot; on the other hand, there can hardly be doubt

that VIII may occur on low ground. Considering that even three centuries of imperfect records are not likely to include the maximum possibility, the general rating of VIII, with proper local exception in either sense, has been retained.

Buffalo is just within the western margin of the area logically assigned high risk from possible large earthquakes on the St. Lawrence rift. Attica, the center of damage in 1929, is near enough to suggest the possibility of serious damage in Buffalo from a larger earthquake centered there or more to the west. However, modern structures on sound rock in the Buffalo area might reasonably be designed against VIII rather than IX. Maximum risk would apply to structures on unconsolidated foundation, particularly on artificial fill or graded material.

New York City should be studied in great detail from the point of view of microregionalization. It is within the range of probable VIII on average ground from a great St. Lawrence earthquake; and the shock in 1884 confirms the presence of a local source, probably offshore, also capable of producing VIII. The solid rock foundation on Manhattan Island probably justifies lower rating locally; whether as low as VI could be decided only by local study. Damage on Long Island in 1884 makes it fairly sure that the Quaternary area there should rate VIII, with probable local spots of IX.

This is an obvious point at which to revert to the problem of the behavior of tall buildings in distant earthquakes. The effects of slow swaying in such circumstances have occasioned much expensive minor damage to the taller buildings in Los Angeles (Steinbrugge and Moran, 1954). These were of course less carefully designed and constructed than the towers of New York. The necessity of allowing for considerable deflection of the latter under wind pressure has resulted in design which should pass through a repetition of the earthquake of 1663, for example, without structural damage, although occupants may be distressed and contents disarranged. Informed engineers should evaluate the probable effects of horizontal oscillation of the ground with periods of from 5 to 10 seconds and amplitudes up to about 5 inches; as is easily seen, this corresponds to maximum accelerations of only about 1 ft/sec.²

EASTERN REGION

Charleston, South Carolina. Regionalization problems arising from the earthquake of 1886 are less difficult with reference to the city itself than in application to the region surrounding and particularly to the west. Careful restudy of surviving evidence, made and published many years after the event by J. R. Freeman (1932), leaves little doubt that destructive effects at Charleston were closely related to ground and to the quality of construction. Maximum rating of IX applies with reason to the worst ground, and particularly to the less consolidated ground toward Summerville, which was taken by Dutton to represent the epicenter because of the strong effects observed there. There seems little reason for giving regionalization ratings higher than actual intensities in 1886, especially since no probable source can be assigned for a distant earthquake likely to produce IX at Charleston. Thus microregionalization for the city could be carried out in much detail simply by using Dutton's and Freeman's data.

Washington, D.C.—Figure 4 includes Washington in the general area of VIII associated with the Appalachian seismicity. There is little history of shaking felt in the city, but in view of the character of the local ground a lower rating would be misleading. Here, if anywhere, it is highly desirable to have regionalization represent probable maxima over very long time intervals.

CENTRAL REGION

Chicago is included with the area of VIII near the Great Lakes. It is near enough to the western part of the St. Lawrence rift to require consideration of the effect of a great earthquake at that distance on tall buildings, in only slightly less degree than for New York City. Ground conditions in general are not of the best; hence the rating of VIII need not be modified.

Kansas City is within range of strong shaking from the earthquakes of southeastern Missouri, although the belt of IX has not been drawn to include it. The grade of VIII may even be reduced to VII where the Paleozoic foundation is especially sound; any local filled or alluvial area should be rated IX.

Tulsa is within the belt rated VIII on the combined basis of the Missouri earthquakes and the local belt of epicenters passing through Oklahoma. A major earthquake at the source of the 1952 Oklahoma shock would be damaging to all but unusually sound structures at Tulsa. Foundation problems are similar to those at Kansas City. Tall buildings might be seriously affected by a large distant earthquake.

WASHINGTON AND OREGON

Seattle is in an area recognized as one of appreciable earthquake risk, on geological evidence and from the known occurrence of small earthquakes long before the damaging shock in 1949. Effects at that time do not justify high risk rating for average ground and construction. Structures damaged were generally old and of poor design and workmanship. As stated in *United States Earthquakes 1949*, VIII was observed "mainly on soft ground with a high water table."

Conditions at *Seattle* provide a partial exception to the general remarks about residential areas on hills. The hilly ground at *Seattle*, consisting chiefly of Quaternary terrace material, under the prevailing conditions of heavy rainfall has a tendency to slide which is accentuated by earthquake shaking. Real-estate promoters and building contractors have located streets and dwellings on steep slopes of this type of ground. Some such structures were damaged by sliding immediately after the 1949 earthquake, others by subsequent motion which may have been initiated at that time.

Portland, Oregon, is in the southern extension of the Puget Sound tectonic depression. Seismic activity is confirmed by numerous small earthquakes such as that of 1953. Ground conditions are in general similar to those at *Seattle*.

CALIFORNIA

Los Angeles sprawls over an area extending northwest beyond the limits of figure 2. The central commercial district is near the center of the old pueblo, on Quaternary terrace and alluvial ground. The industrial center adjoins on the south and southeast, where the ground is largely alluvial near the bed of the Los Angeles River. The many separate business centers, some of which were formerly distinct towns, are mostly also on similar foundation. As already discussed, the rating varies from VII to IX.

Until lately the city enforced a building-height limit of 13 stories, originally intended not as an earthquake safety measure but to prevent further congestion in narrow streets. An exception was made for the tower of the City Hall. The general limit has now been raised to 20 stories. The writer considers this an ill-advised action, taken in the face of evidence of damage to the existing taller structures by the earthquake of 1952, and the record of larger motions of the same kind in 1857. Any new tall structures will presumably be comparatively well designed and built; but they may have to face a much severer test than is likely for tall buildings in New York City.

Riverside is an example of an extremely complex microregionalization problem. The writer has been misquoted as saying that *Riverside* as a whole is safe against earthquakes. This is a misleading half-truth.

Some of the residential area of the city is on hills of solid granitic rock. An auxiliary station of the southern California seismological network is founded on this granite, and has shown relatively low amplitudes in recorded earthquakes, comparable with those on granite at Pasadena, thus confirming a rating of VI on these hills.

On the other hand, the flat central district of *Riverside*, and a large area in the city limits to the south and southeast, is on alluvial or terrace ground; considering the proximity to active faults and to the granitic hills near which motion may be expected to be accentuated, rating of probable intensity IX is justified. Insurance organizations handling risks in *Riverside* should also consider the weak and superannuated character of some of the structures now used for business.

San Diego has been discussed briefly in connection with figure 3. There has been a general impression that earthquake risk does not exist at *San Diego*, historical records to the contrary being forgotten or ignored. Older structures were erected with no close attention to soundness. During and since World War II, population has increased enormously, and the city area has expanded at a pace hardly consistent with careful construction and inspection. Fortunately, much of this expansion has been over the higher ground rated at VII.

San Francisco in 1906 provided one of the classical instances of effect of varying ground on earthquake intensity (Lawson *et al.*, 1908). Although the earthquake damage was partly obscured by the subsequent fire, it was established that severe shaking, corresponding to intensity IX, occurred chiefly on the area of filled land reclaimed from *San Francisco Bay*, including the lower part of Market Street in the business center. Small isolated patches of fill and alluvium also showed damage indicating IX, while many of the residences on adjoining hills were nearly undamaged.

As indicated to some extent in figure 3, the vicinity of San Francisco provides a complicated situation for microregionalization. The effect of ground cannot be made the nearly exclusive criterion, as in most of the Los Angeles area, and the general level of rating must be raised because of the proximity of the San Andreas fault, which passes just outside the city limits about 8 miles from the business center. Ground varies from the relatively sound Mesozoic of the hills to the unstable extreme of filled ground just mentioned, with tide flats and swampy areas adjacent to San Francisco Bay, and sand dunes on the coast.

CONCLUSIONS

The tentative and incomplete nature of the results in this paper is obvious. The following conclusions seem justifiable:

1. Regionalization, as presented in this paper, is satisfactory only where microregionalization is possible. Only microregionalization can adequately meet engineering requirements.

2. Microregionalization is only possible where detailed large-scale geological maps are available, where active faults are known, and where actual seismicity is high enough so that historical documents and instrumental registration give an adequate idea of local earthquake geography.

3. Small-scale regionalization maps covering large areas are satisfactory only when they represent generalization of the results of microregionalization. They should serve as general index maps, from which the engineer or planning authority should pass to microregionalization maps for the localities where construction is intended.

4. Microregionalization is practicable for most of the settled parts of California. For less settled areas, data on seismicity are adequate, so that microregionalization there waits only on the availability of detailed geological maps.

5. Regionalization can now be carried out for the whole of California, but involves some very rough estimates in desert and mountain areas.

6. Regionalization for the United States, as attempted in this paper, is more difficult than for the USSR, and such maps as figure 4 are open to every sort of challenge and question.

APPENDIX

The following description of effects at grades VI–IX of the Modified Mercalli scale (M.M.) of 1931 is extracted from the original publication (Wood and Neumann, 1931). Marginal notes in brackets give approximate equivalents on the older Rossi-Foré scale (R.F.).

A suggested rewording of the M.M. scale, with comments and discussion, is given by Richter (1958*b*, pp. 136–139, 650–652).

VI	<i>Felt by all, indoors and outdoors.</i>
	<i>Frightened many, excitement general, some alarm, many ran outdoors.</i>
	<i>Awakened all.</i>
(VI to VII R.F.)	<i>Persons made to move unsteadily.</i>
	<i>Trees, bushes, shaken slightly to moderately.</i>
	<i>Liquid set in strong motion.</i>
	<i>Small bells rang—church, chapel, school, etc.</i>
	<i>Damage slight in poorly built buildings.</i>
	<i>Fall of plaster in small amount.</i>
	<i>Cracked plaster somewhat, especially fine cracks, chimneys in some instances.</i>

- Broke dishes, glassware, in considerable quantity, also some windows.*
Fall of knick-knacks, books, pictures.
Overtured furniture in many instances.
Moved furnishings of moderately heavy kind.
- VII *Frightened all*—general alarm, all ran outdoors.
 Some, or many, found it difficult to stand.
 Noticed by persons driving motor cars.
Trees and bushes shaken moderately to strongly.
 Waves on ponds, lakes, and running water.
 Water turbid from mud stirred up.
 Incaving to some extent of sand or gravel stream banks.
 Rang large church bells, etc.
 Suspended objects made to quiver.
- (VIII—
R.F.) *Damage negligible* in buildings of good design and construction, *slight* to moderate in well-built ordinary buildings, *considerable* in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.
Cracked chimneys to considerable extent, *walls* to some extent.
Fall of plaster in considerable to large amount, also some stucco.
Broke numerous windows, furniture to some extent.
 Shook down loosened brickwork and tiles.
 Broke weak chimneys at the roof-line (sometimes damaging roofs).
Fall of cornices from towers and high buildings.
 Dislodged bricks and stones.
Overtured heavy furniture, with damage from breaking.
Damage considerable to concrete irrigation ditches.
- VIII *Fright general*—alarm approaches panic.
 Disturbed persons driving motor cars.
Trees shaken strongly—branches, trunks, broken off, especially palm trees.
 Ejected sand and mud in small amounts.
 Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters.
- (VIII+
to
IX—
R.F.) *Damage slight* in structures (brick) built especially to withstand earthquakes.
Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling.
Fall of walls.
Cracked, broke, solid stone walls seriously.
Wet ground to some extent, also ground on steep slopes.
Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
Moved conspicuously, overturned, very heavy furniture.
- IX Panic general.
Cracked ground conspicuously.
- (IX+
R.F.) *Damage considerable* in (masonry) structures built especially to withstand earthquakes: threw out of plumb some wood-frame houses built especially to withstand earthquakes;
great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames;
 serious to reservoirs; underground pipes sometimes broken.

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